NASA/CP–20220000594

NASA Earth Science Technology Office (ESTO)
Advanced Information Systems Technology (AIST)

New Observing Strategies (NOS)

Annual Technical Reviews

Jacqueline Le Moigne

January 2022

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Jacqueline Le Moigne
Goddard Space Flight Center, Greenbelt, MD

January 2022

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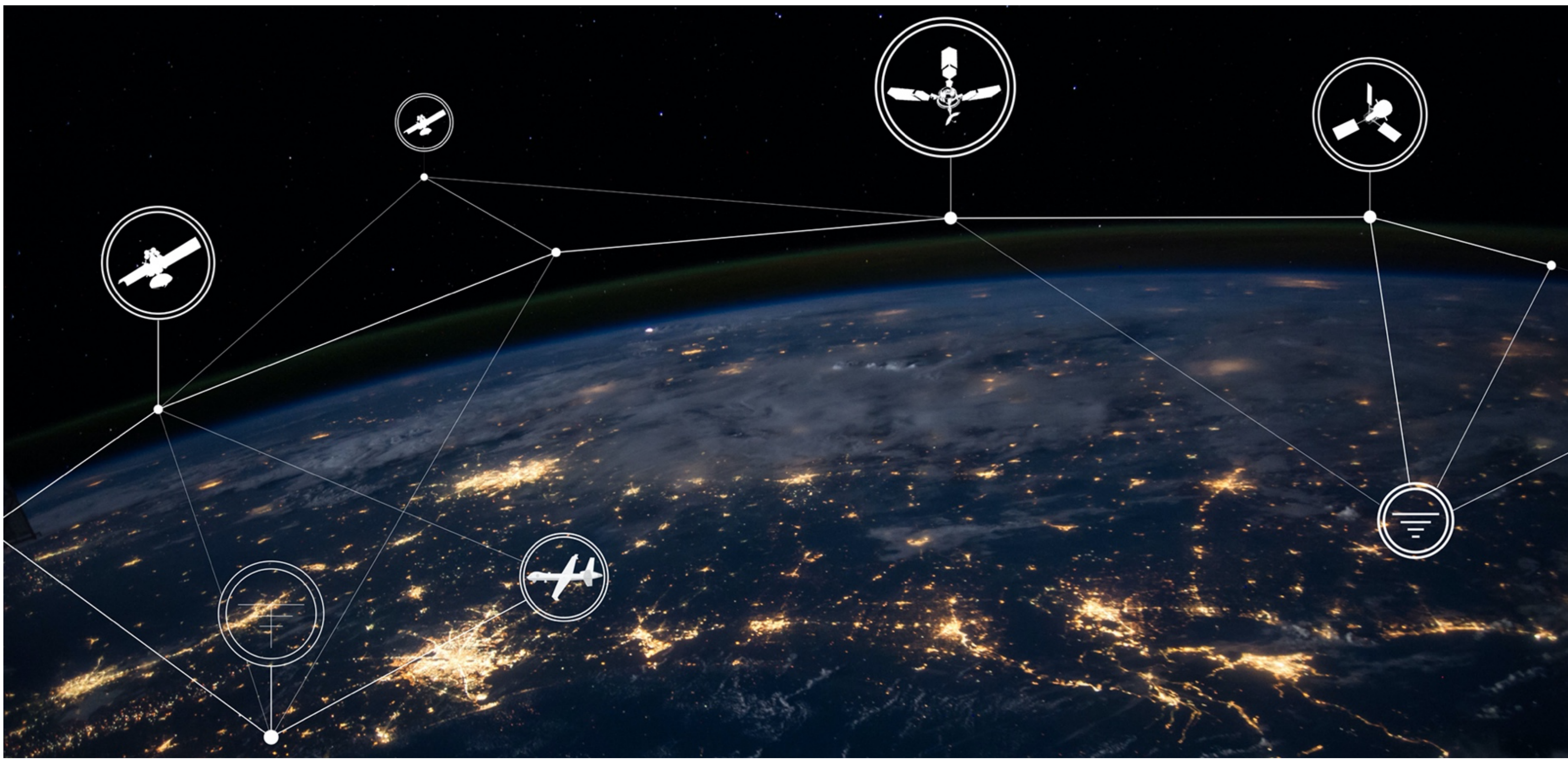
Advanced Information Systems Technology (AIST)

2022 New Observing Strategies (NOS) Annual Reviews



Held Virtually on January 07, 2022

Also at:
https://esto.nasa.gov/files/AIST_NOS_Group_Annual_TechRev_January7_2022.pdf

Friday, January 7, 2022								
New Observing Strategies (NOS)								
Tech	**Science**	**End Date**	**Type**	**Org**	**Name**	**Title**	**Start**	**Stop**
					Le Moigne	Introduction	1:00 PM	1:20 PM
OSSE / Modeling Systems	Snow / Water & Energy	8/23/2022 -	2nd Annual	UCAR	Gutmann	Future Snow Missions: Integrating SnowModel in LIS	1:20 PM	1:40 PM
Modeling systems / data fusion / OSSE	Hydrology / Water & Energy	9/30/22	2nd Annual	UMD	Forman	Next Generation of Land Surface Remote Sensing	1:40 PM	2:00 PM
OSSE / SW Architecture	Weather / Clouds & Aerosols	1/31/22	Final	JPL	Posselt	Parallel OSSE Toolkit	2:00 PM	2:20 PM
Mission Planning tool / Constellation planning testbed architecture		4/30/22	2nd Annual	Stevens Inst.	Grogan	Integrating TAT-C, STARS, and VCE / NOS Testbed Architecture	2:20 PM	2:40 PM
Break							2:40 PM	2:50 PM
Sensor Web / Autonomy / ML	Soil Moisture / Water & Energy	7/31/22	2nd Annual	ARC	Nag	D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions	2:50 PM	3:10 PM
Onboard processing, Cube-SmallSats	Weather / Winds	1/31/22	Final	Carr Astro. Corp	Carr	StereoBit: Advanced Onboard Science Data Processing to Enable Earth Science	3:10 PM	3:30 PM
Sensor Web / UAV operations	Hydrology / Water & Energy	6/30/22	2nd Annual	USC	Moghaddam	SPCTOR: Sensing Policy Controller and OptimizeR	3:30 PM	3:50 PM
Ground Station as a service / SW Architecture		11/30/21	Final	LaRC	Nguyen	Ground Stations as a Service (GSaS) for Direct Broadcast Satellite Data	3:50 PM	4:10 PM

Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit SnowModel in LIS

Ethan Gutmann (PI, NCAR),
Glen Liston (Co-I, CSU), Carrie Vuyovich (Co-I, GSFC),
Barton Forman (Co-I, UMD), Jessica Lundquist (Co-I, UW)

AIST-18-0045 Annual Technical Review
January 7th, 2022

Team listing: Ross Mower (NCAR), Alessandro Fanfarillo (NCAR), Andy Newman (Co-I, NCAR), Adele Reinking (Co-I, CSU), Kristi Arsenault (Co-I, GSFC/SAIC), Melissa Wrzesien (GSFC/USRA)

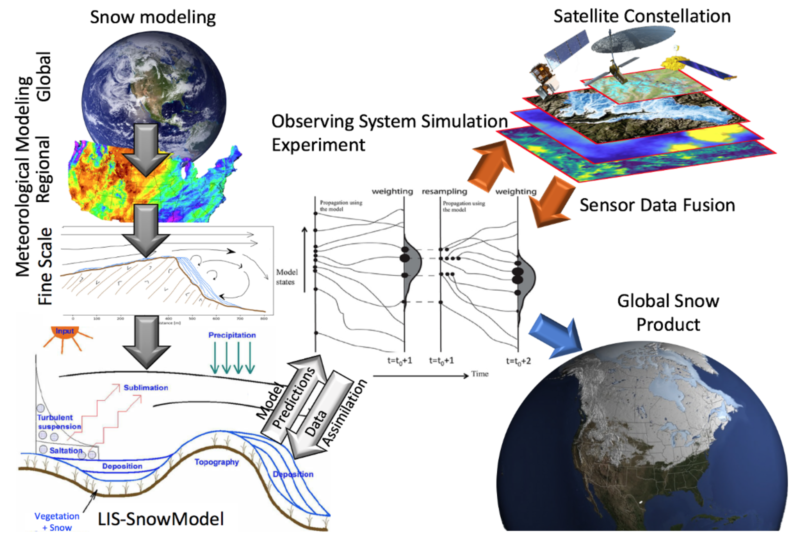
Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit SnowModel in LIS

PI: Ethan Gutmann, National Center for Atmospheric Research

Objectives

Develop an OSSE to improve analysis of snow mission design cost-benefit tradeoffs and extend the NASA Land Information System Framework (LISF) to simulate critical sub-km scale snow variations by:

- Developing a modeling system to produce a realistic fine-scale simulation of snow spatial patterns
- Enhancing LIS-SnowModel system to be capable of continental scale sub-km grid simulations
- Improving local meteorology forcing data for LISF in complex terrain
- Parallelization and optimization for large-domain simulations



Snow Modeling OSSE and Data-Fusion Framework

Approach

Extend the NASA Land Information System Framework (LISF) to simulate critical snow processes:

- Incorporate SnowModel's MicroMet in LISF to enhance the surface meteorological fields produced by LISF
- Add SnowModel's SnowPack and snow redistribution capabilities to extend the snow modeling capabilities in LISF.
- Implement and optimize multi-node parallel computing capability into LISF-SnowModel to permit large, high-resolution simulations.
- Utilize the new LISF-SnowModel capabilities for the NASA-SnowEx Snow Ensemble Uncertainty Project (SEUP) and a dedicated Observing System Simulation Experiment (OSSE).

Key Milestones

- MicroMet routines integrated in LISF 12/20
- SnowModel is used in LIS to complete a simulation 03/21
- 30-year continental domain SnowModel simulation completed 03/22
- Continental domain LIS-SnowModel simulations used with the synthetic observation operator as the Nature run for NASA-SEUP snow OSSE. 08/22

$\mathrm{TRL}_{in} = 2$ **$\mathrm{TRL}_{current} = 4$**

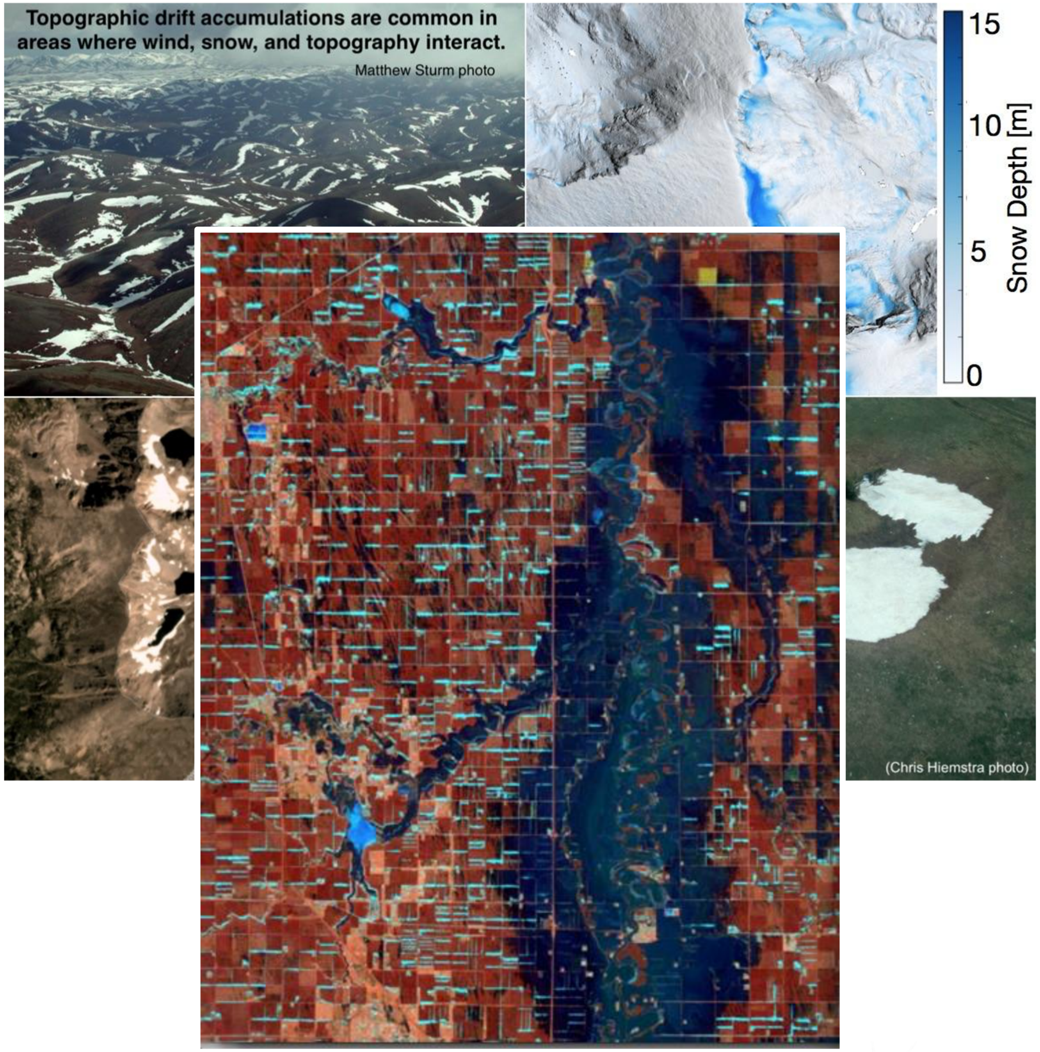
Co-Is/Partners: B. Forman, UMD; G. Liston, A. Reinking, CSU; J. Lundquist, UW; A. Newman, NCAR; C. Vuyovich, K. Arsenault, S. Wang, S. Kumar, GSFC

Presentation Contents

- Background and Objectives
- Technical and Science Advancements
- Summary of Accomplishments and Future Plans
- Actual or Potential Infusions and Collaborations
- Publications - List of Acronyms

Why do we need a spatially explicit representation of snow in LIS?

- LIS snow is used for mission planning and model-data fusion
- The representation of snow in LIS now is one dimensional
- Real snow is extremely heterogeneous
- Variability comes from preferential deposition / redistribution / melt
- Occurs on scales of 10-100 m, but has impacts over 10-100 km
- Using LIS as a planning tool for future snow missions thus likely undervalues high spatial resolution and overvalues methods that work well for shallow snowpacks.



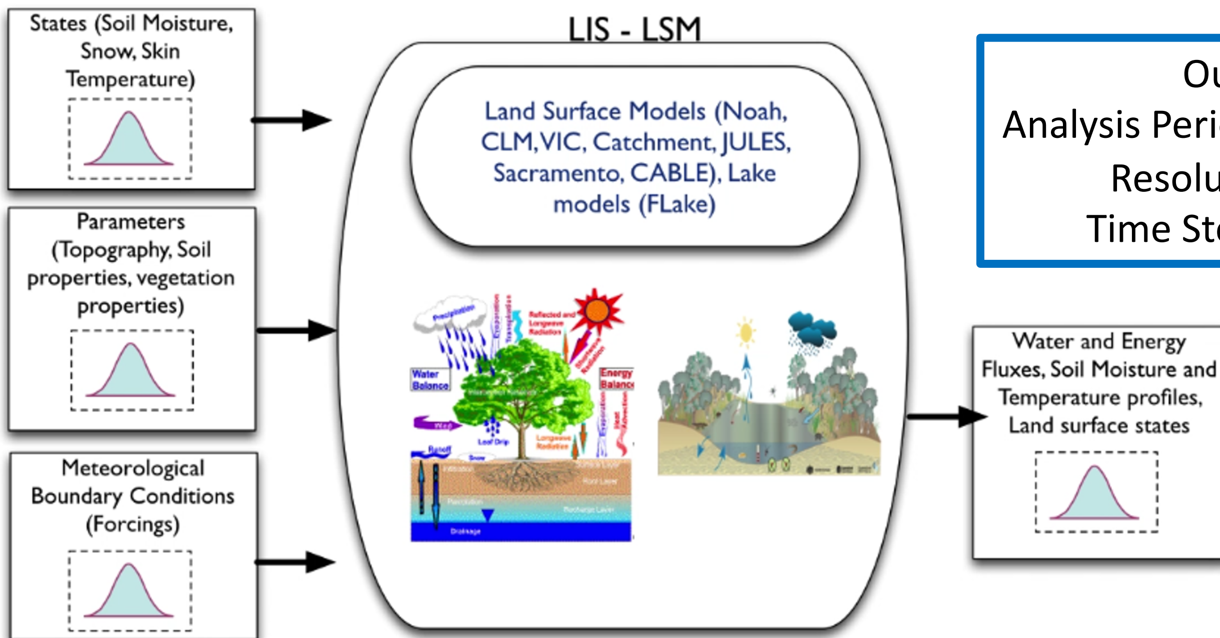
LIS and Snow Ensemble Uncertainty Project

Use the NASA Land Information System (LIS) framework to run an ensemble of models and forcing datasets to characterize SWE uncertainty across North America to identify regions and temporal periods of high variability.

Downscaling

3 Forcings:

MERRA2
GDAS
ECMWF



Output:
Analysis Period: 2009 – 2017
Resolution: 5km
Time Step: 3 Hours

SCF
SWE
Evaporation
Surface runoff
Soil Moisture
Rainfall
Snowfall

4 LSMs:

Noah-MP, Noah 2.71, Jules, CLSMF 2.5

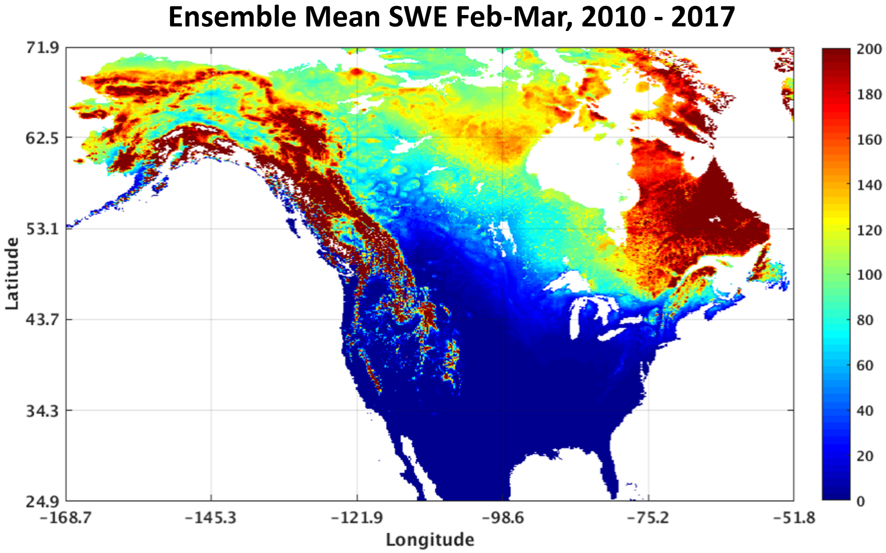
SEUP Initial Results

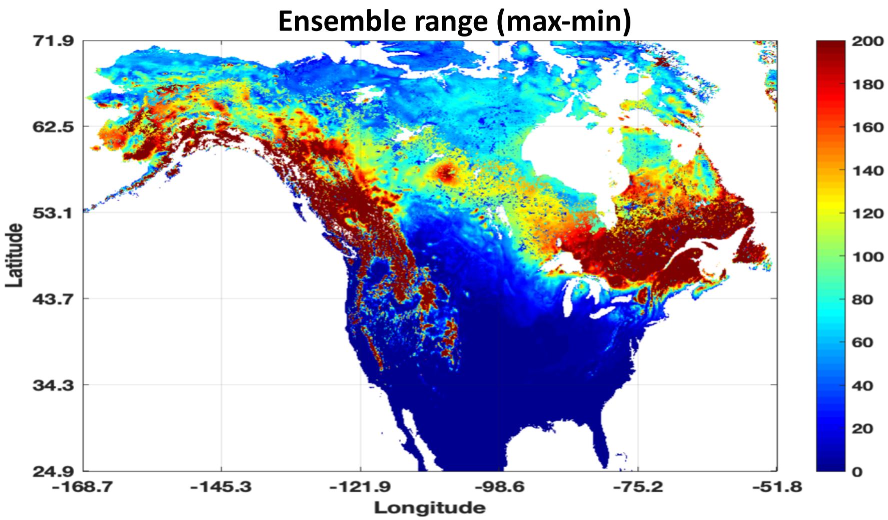
1. Tundra region: 43 – 67% of total N. America Snow Water Storage (SWS), high variability in ensemble estimates of SWS.

2. Evergreen/Taiga regions: 17 – 27% of total N. America SWS, with high variability in estimates of SWS and SWE

3. Mountain regions have much greater amount and variability in Snow Water Equivalent (SWE) than non-mountain regions

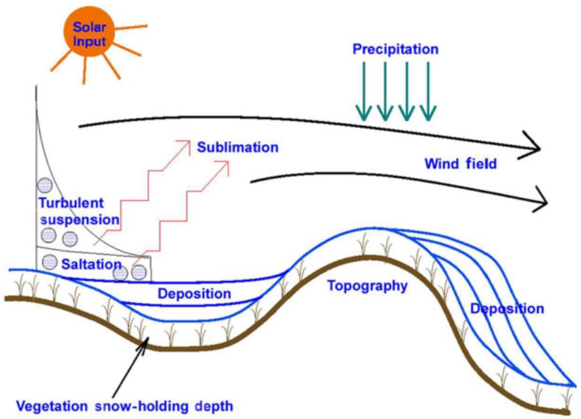
4. About 75% of the spread stems from the choice of LSM, rather than forcing, though it varies by location.

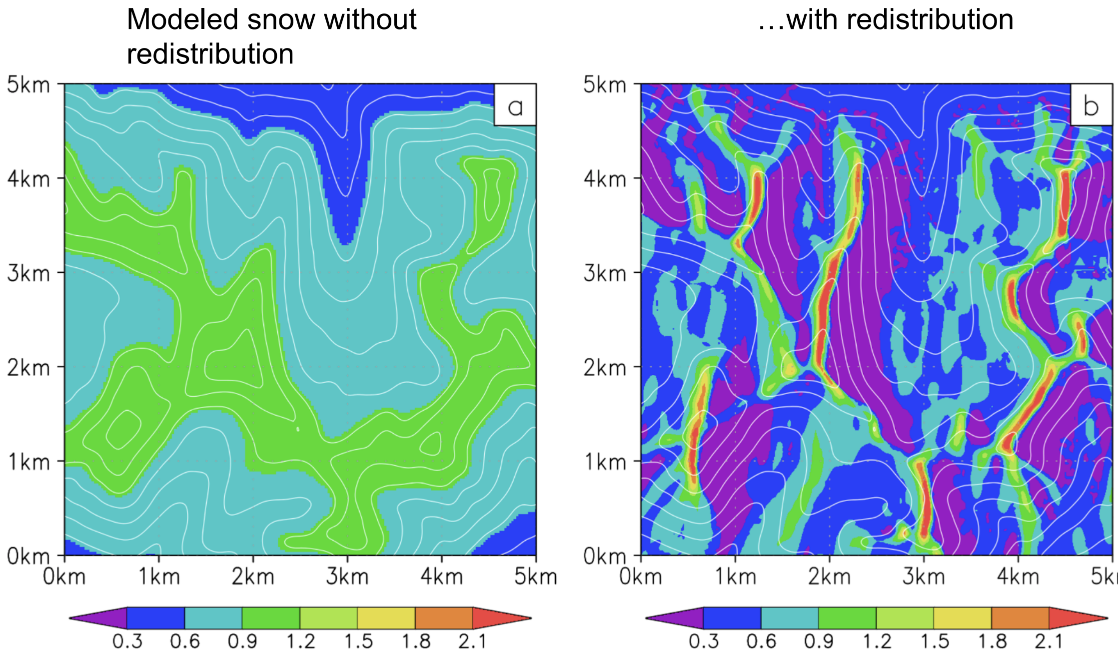




Objective: Improve LIS Snow modeling capabilities

- Couple SnowModel into LIS
  - Snow redistribution capabilities
  - MicroMet: terrain influenced wind, radiation, temperature,…
- Parallelize SnowModel in LIS
- Couple SnowModel to Noah-MP in LIS
- Run continental domain Snow OSSE with LIS-SnowModel





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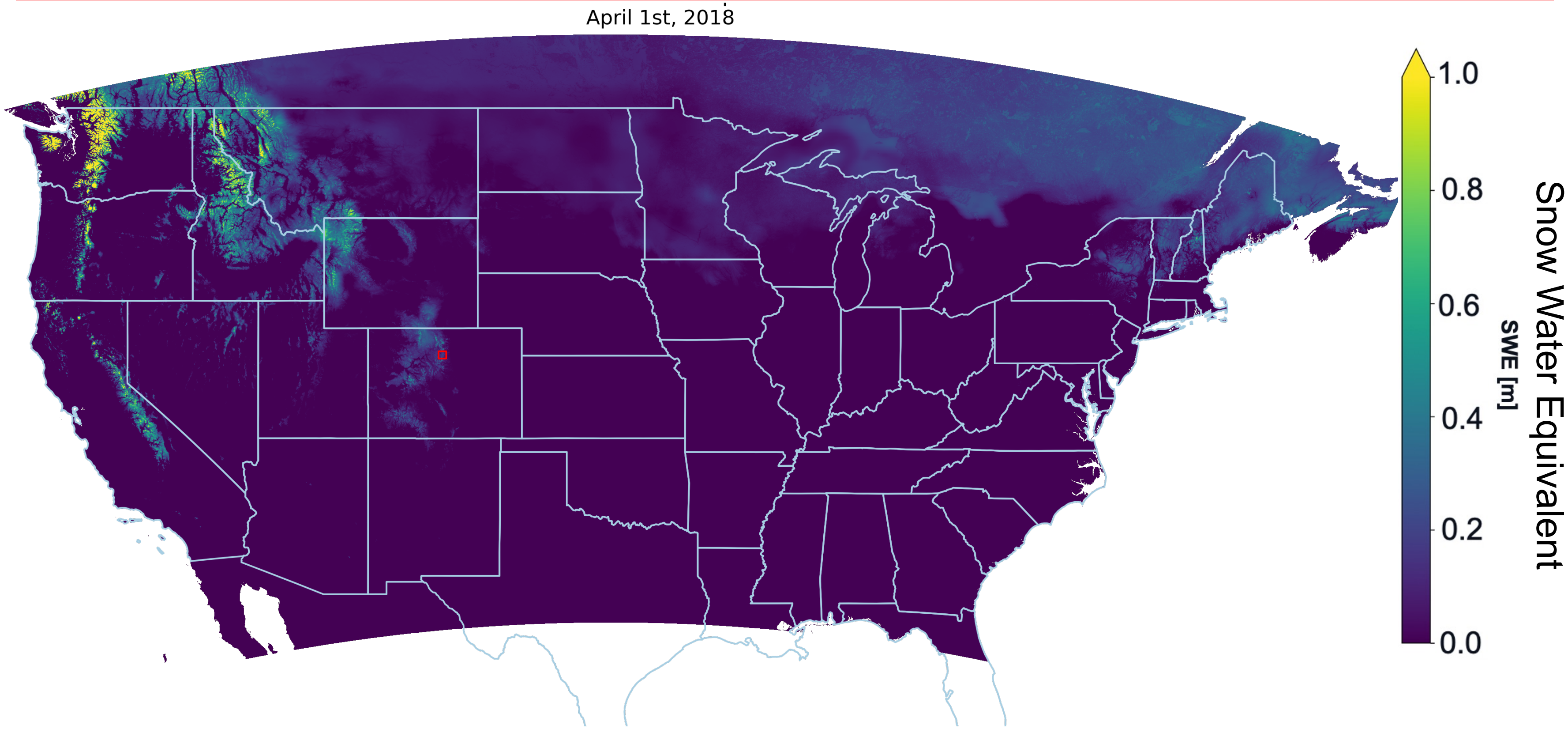
Technical and Science Advancements



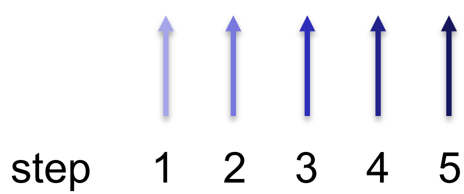
- SnowModel parallelized to run very large domains in distributed memory
  - Snow transport algorithm has been parallelized
  - All memory allocations in SnowModel optimized for parallel sub-domains
  - File IO has been parallelized in SnowModel to remove bottleneck
  - NetCDF IO has been developed for SnowModel to improve IO efficiency
  - Initialization routine has been optimized to scale as O(n) instead of O(n*m)

Parallel Algorithm Development

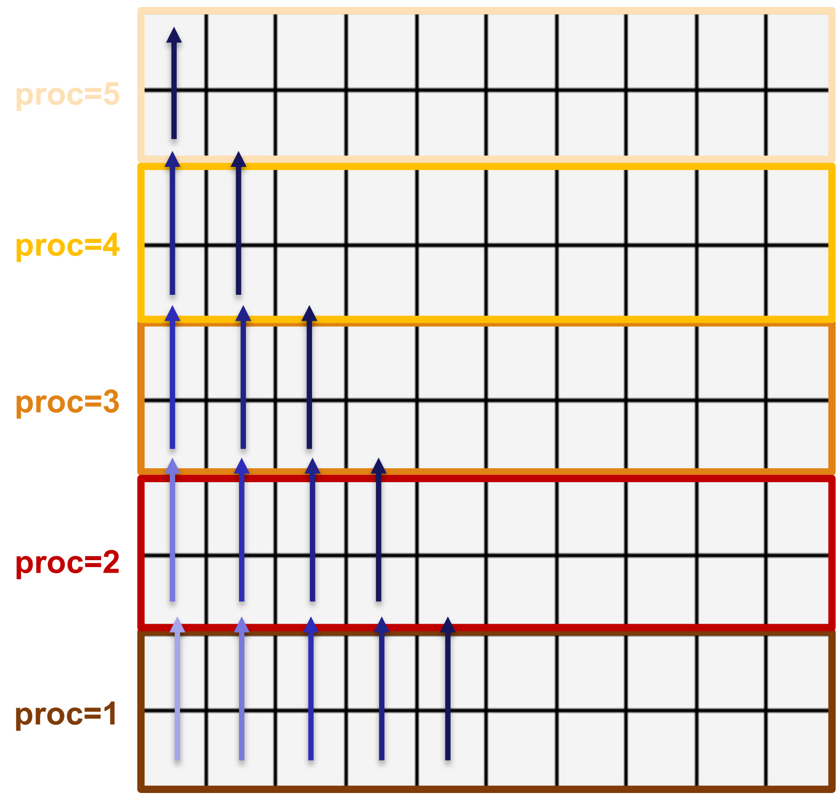
Innovative Parallelization Strategy

Approach

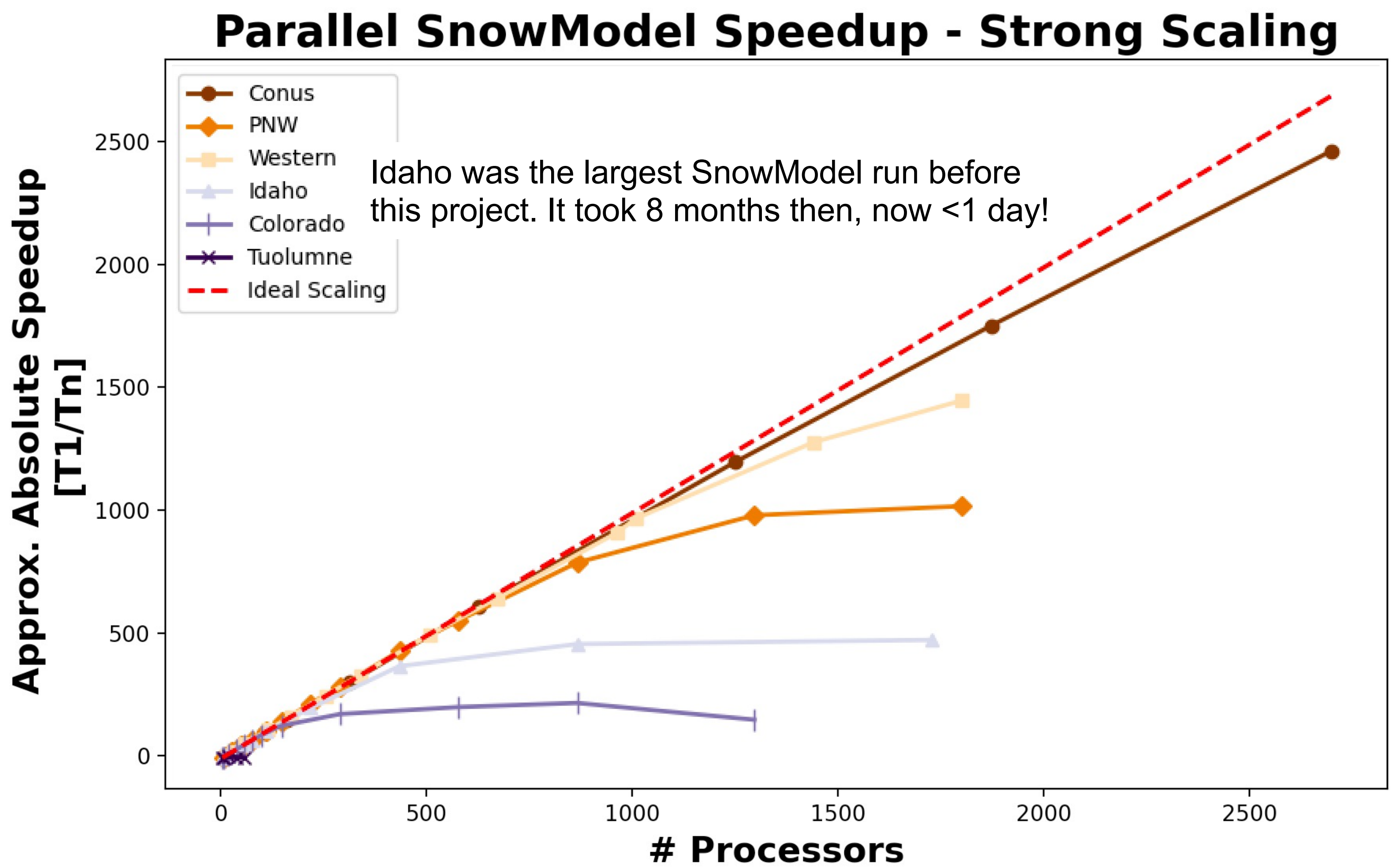
- 1-D decomposition
  - communication is localized!
- Use of Partitioned Global Address Space (PGAS) Coarray Fortran
- Each process depends on its neighbor
- That dependency can be met column by column
- Piecewise asynchronous communication permits process 5 to start before process 1 finishes
  - Alternative process 2 does not start until process 1 finishes
  - All processes iterate to convergence



Example of SnowModel grid decomp. w/ 5 processors



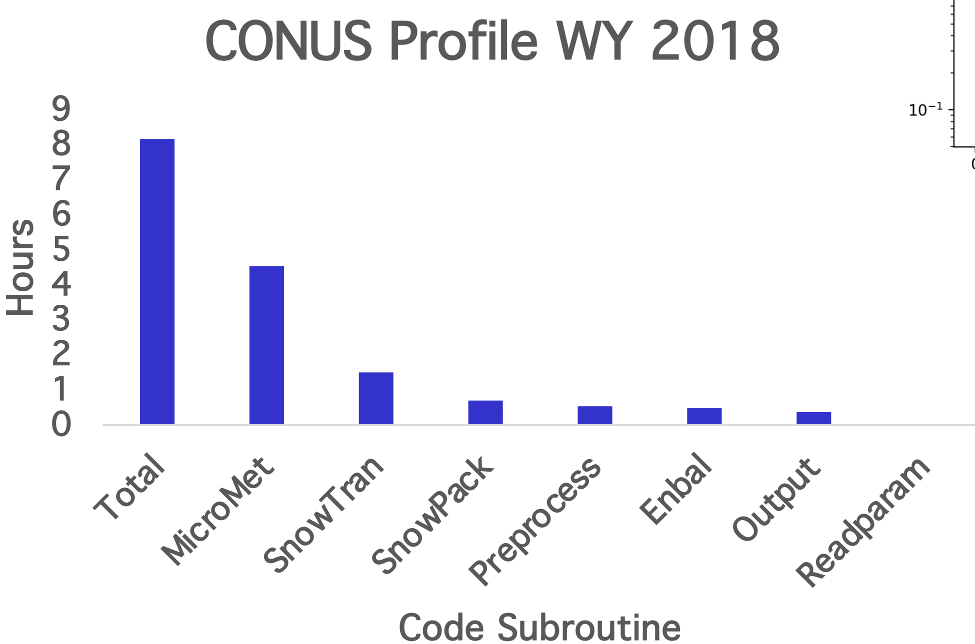
Efficient Parallel Scaling to >2500 cores



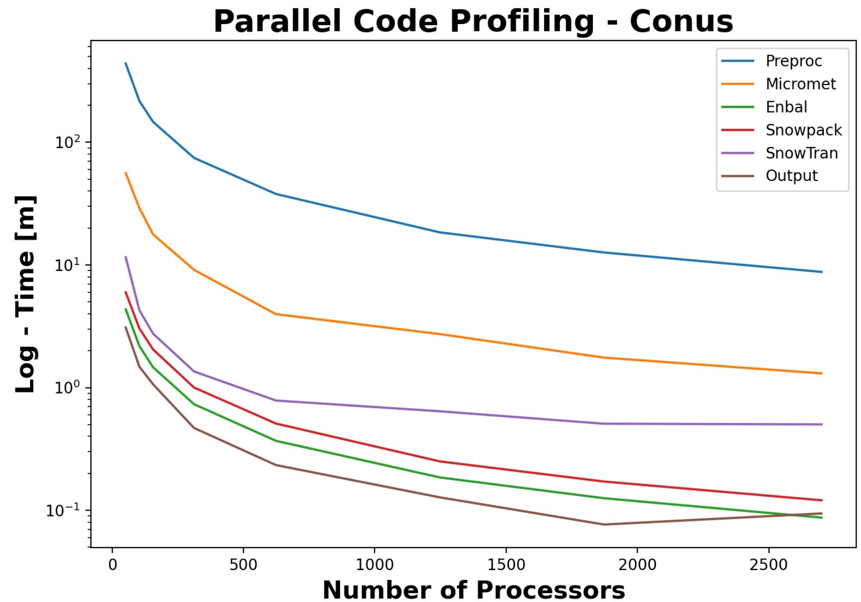
Profiling Reveals Scaling and Serial Bottlenecks

Micromet is the largest cost over a long model integration

This is due primarily to file reads



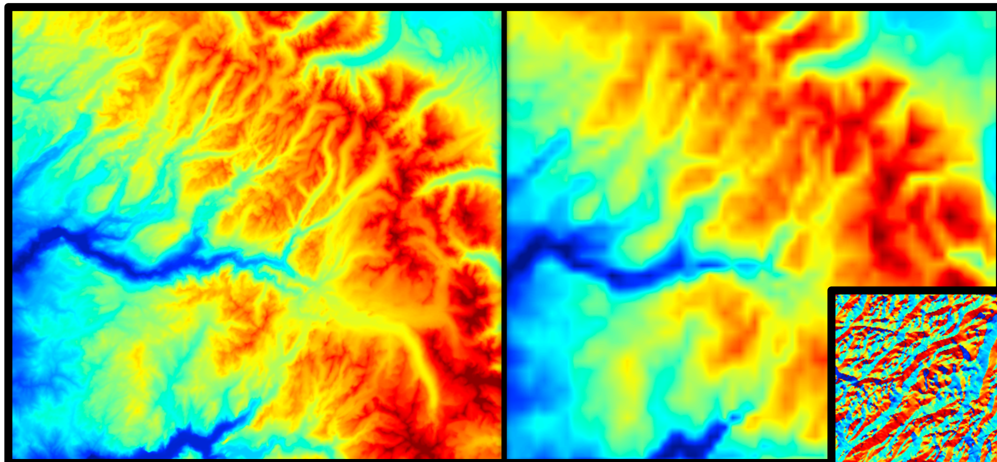
Short Simulation



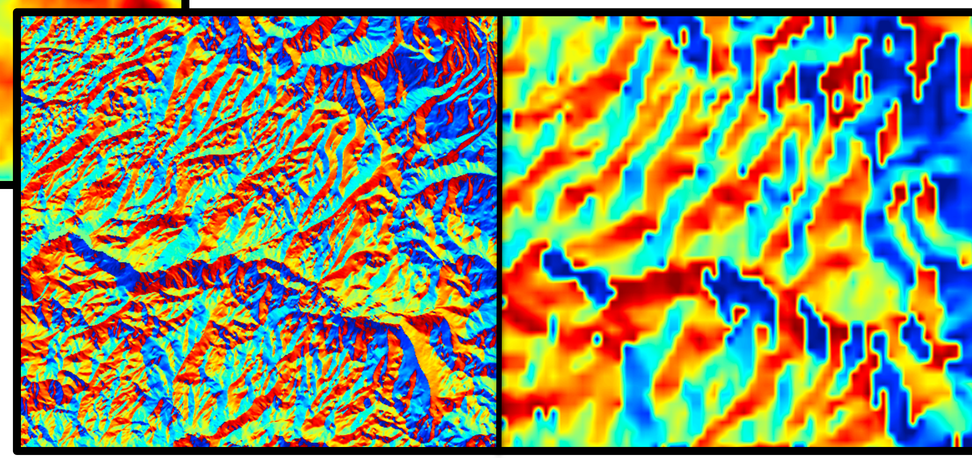
Output and SnowTran start to show poor scaling on >2000 cores

Improved handling of input data in LIS

High-resolution DEM in LIS Previous 1km DEM

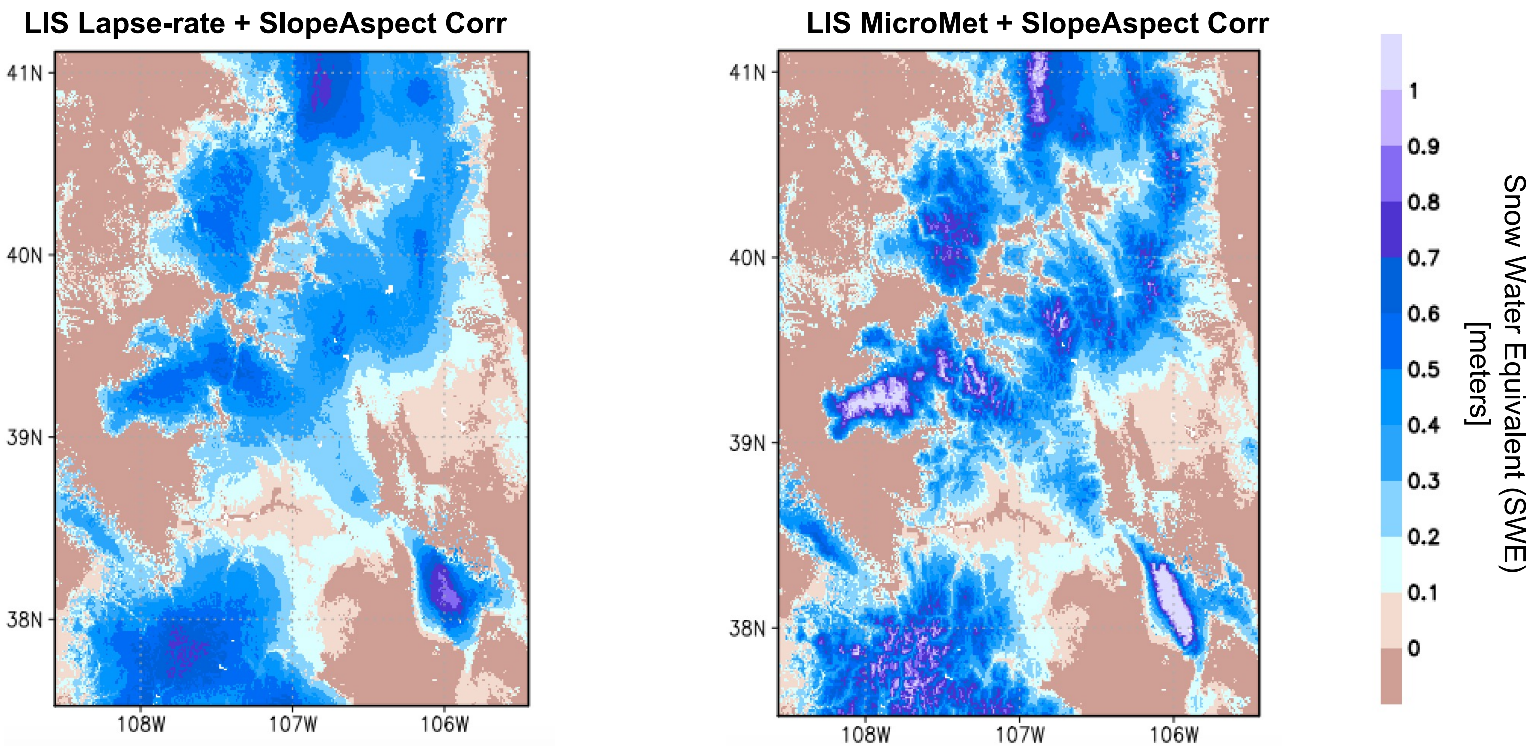


High-Resolution DEM and Aspect



- LIS-SnowModel parallelization and coupling with NoahMP
  - LIS-SnowModel can run larger domains
  - LIS LDT pre-processor parallelized to handle new, higher-resolution input files
  - LIS can couple SnowModel to the NoahMP land surface hydrology model
  - Major effort to parallelize LIS model parameter IO

Improved meteorology for all LSMs in LIS

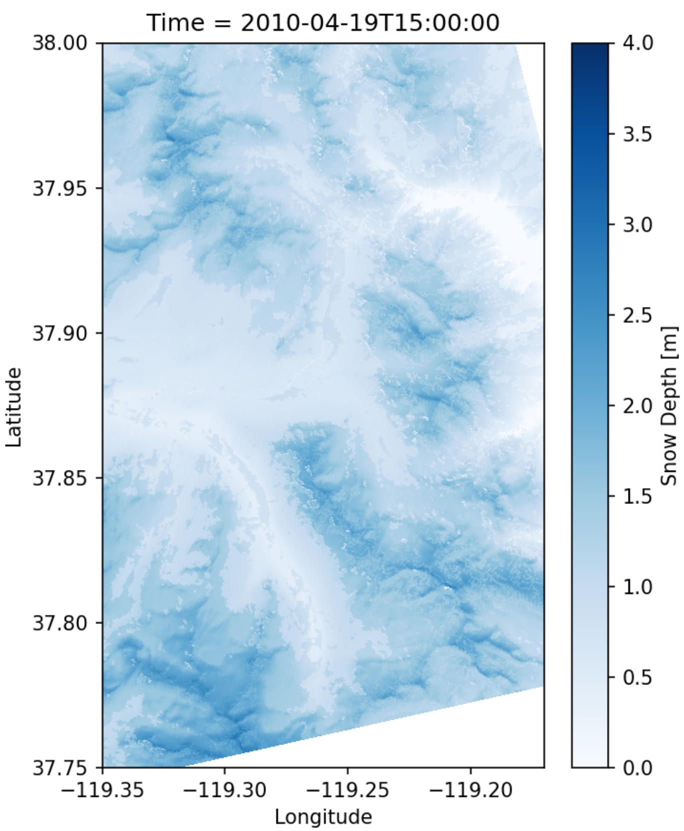


LIS-NoahMP401 runs on 1km grid using standard LIS meteorological corrections (left) and Micromet corrections (right)

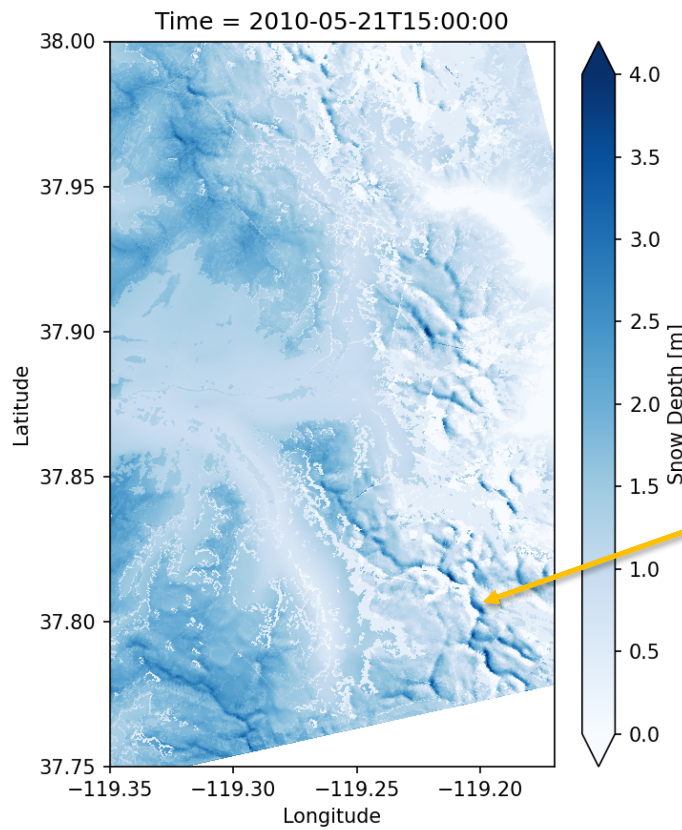
- SnowModel "micromet" routines available for other Land Surface Models in LIS!

Improved meteorology for all LSMs in LIS

Developed new WRF reader for LIS

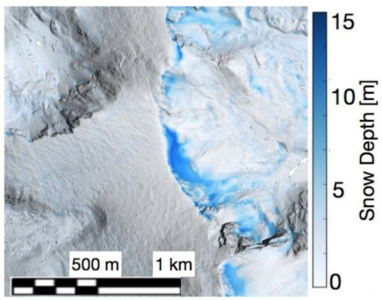


SnowModel simulation with NLDAS2 meteorology



SnowModel simulation with new WRF meteorology

Realistic scour-deposition couplets compare with lidar (below)



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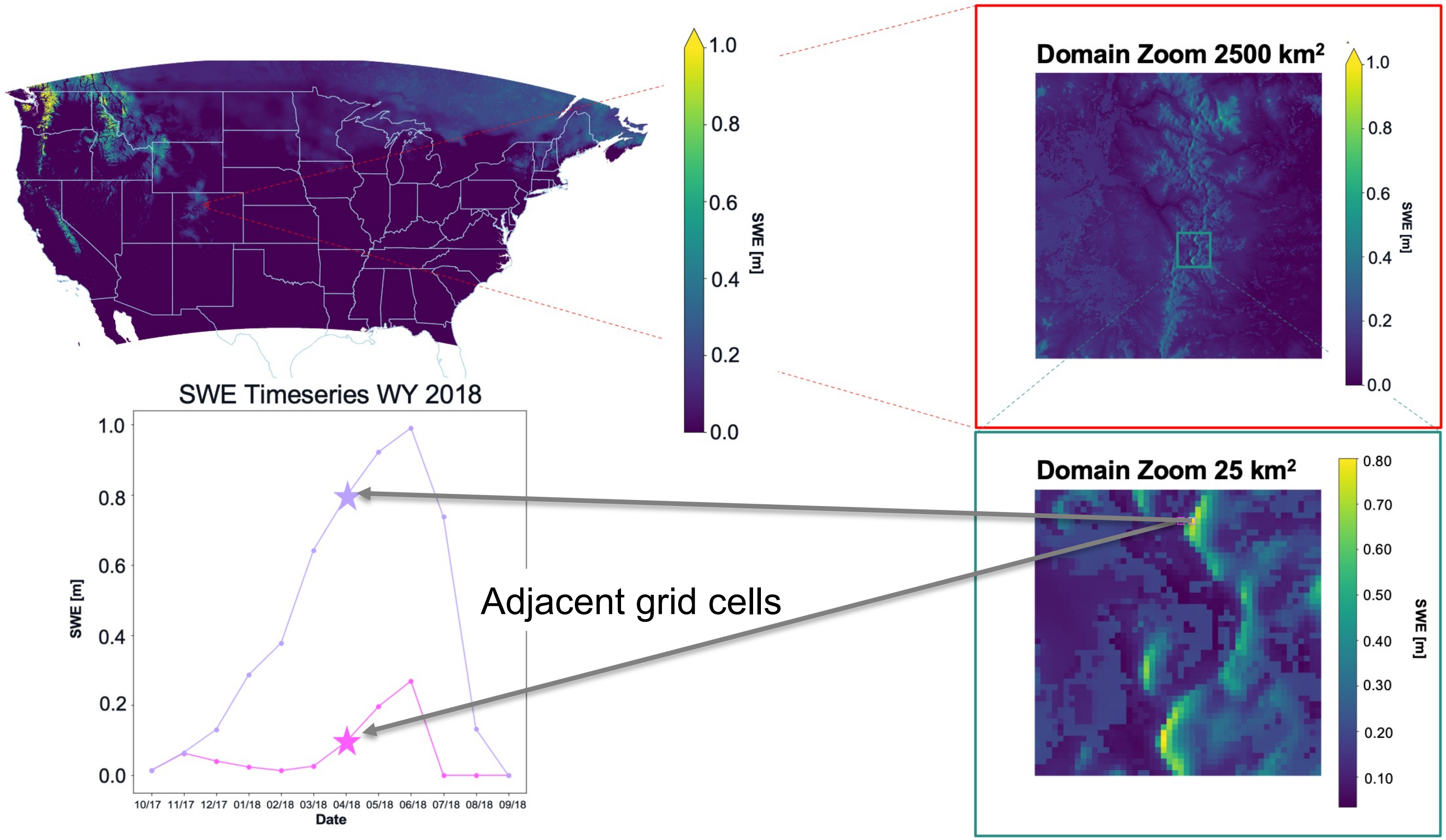
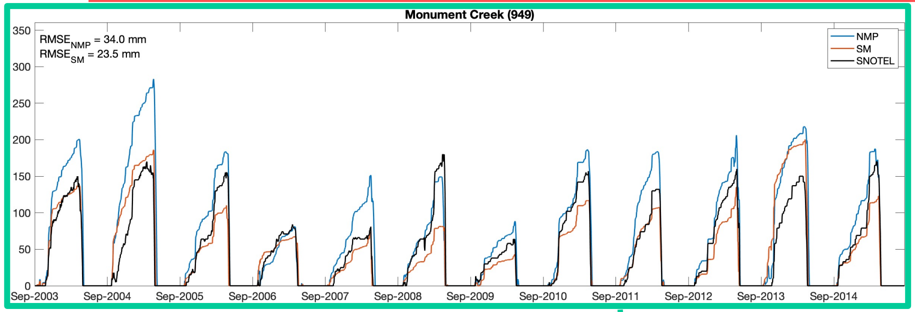
CONUS Domain 100 m grid SnowModel Simulation

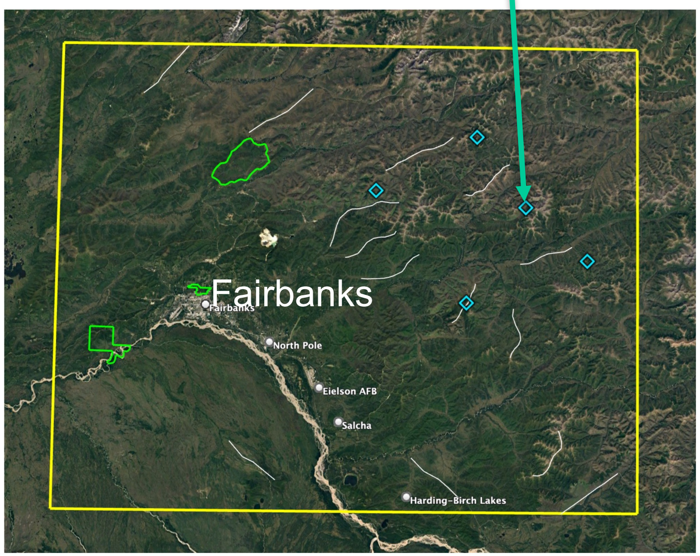
Largest domain ever run : ~60,000 x 30,000 grid cells

Maps of Snow Water Equivalent (SWE)



LIS-SnowModel used in SnowEx Alaska SEUP





Model compared to Gamma aircraft flight SWE

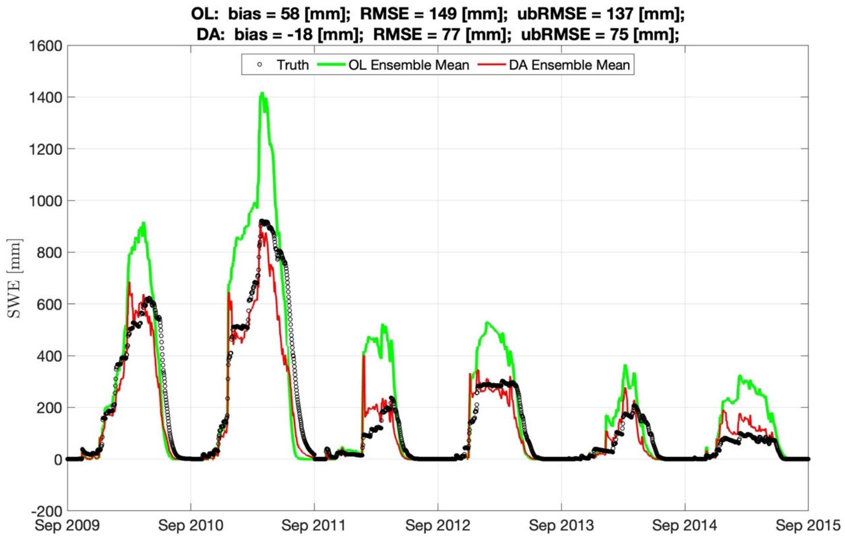
	Model	Mean SWE Bias (mm)	Mean SWE RMSE (mm)	Mean SWE MAE (mm)
(NMP)	NoahMP	72.49	87.38	72.88
(SM)	SnowModel	28.44	53.10	44.35
(NMP-CR)	NoahMP-Crocus	67.55	81.99	70.08
(CR)	Crocus	64.67	83.87	70.84

SWE comparison over 5 SNOTEL stations for water years 2004-2015

Mean RMSE (mm) *Italics indicate best performance*				
Stations	NMP	SM	NMP-CR	Crocus
Little Chena Ridge	49.0	33.1	33.6	*29.9*
Monument Creek	34.0	*23.5*	40.3	47.7
Mt. Ryan	52.6	30.2	33.1	*27.7*
Munson Ridge	35.4	26.2	*25.8*	28.2
Teuchet Creek	31.4	*19.1*	30.7	29.9

- LIS-SnowModel has been used in SnowEx Alaska field campaign planning activities
  - New Snow model ensemble project includes LIS-SnowModel
  - SnowModel is the most accurate of the model simulations to date
  - SnowModel is also the most independent (least similar) to the other models

Summary of Accomplishments and Future Plans



OSSE framework tested over Tuolumne basin with LIS-SnowModel.

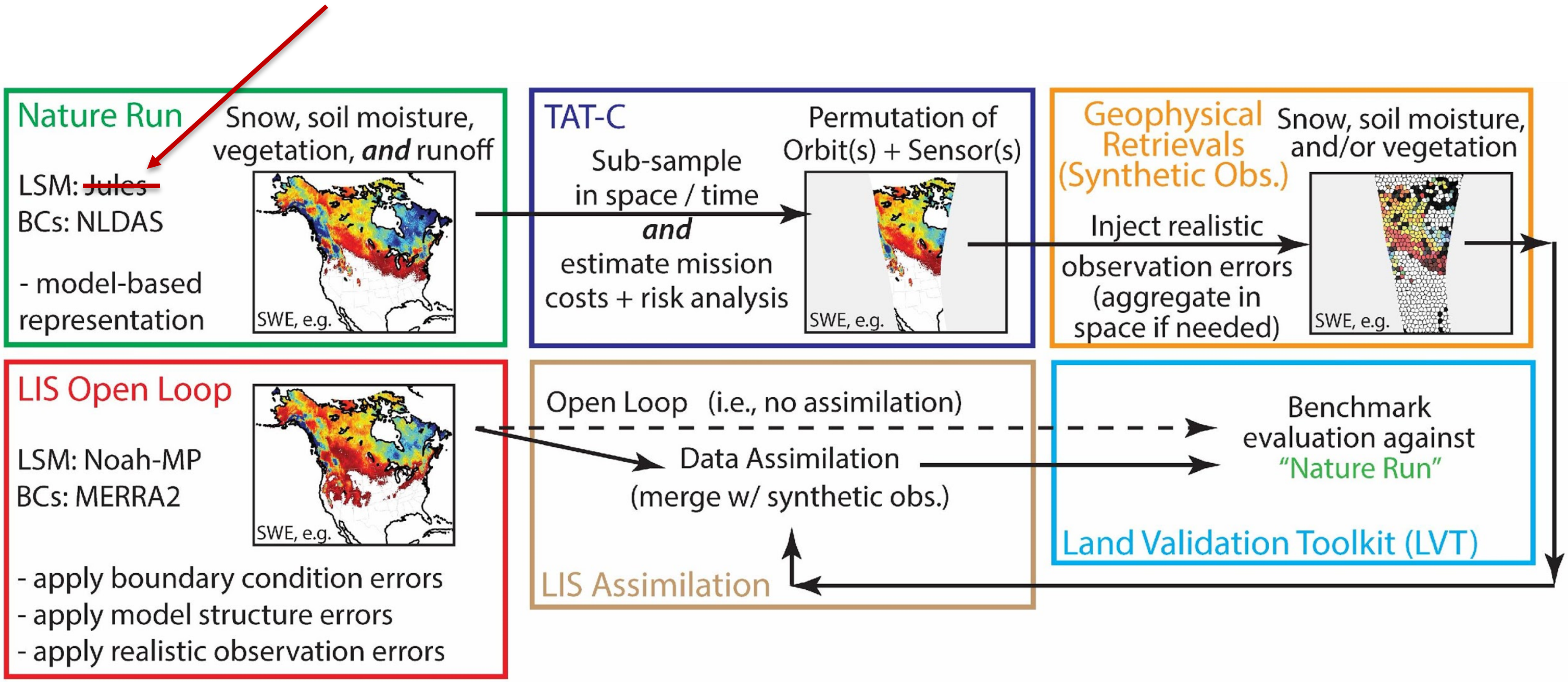
Scaling to CONUS is the primary remaining challenge

- 30-year SnowModel integrations over CONUS domain at 100 m
- LIS-SnowModel has a memory bottleneck that is being addressed, and a file output bottleneck that affects all models
- Performing the OSSE over CONUS with LIS-SnowModel-NoahMP coupling as originally planned requires the above bottlenecks to be solved
  - Mitigation options include:
    - Running a smaller domain, or set of domain as discussed in our proposal
    - Running SnowModel offline and using snow in LIS-NoahMP coupling

ESTO Earth Science Technology Office

Summary of Accomplishments and Future Plans

Bringing SnowModel into a continental scale OSSE



Innovation: **``fraternal twin" experiment rather than "identical twin"** (AIST-16-0024)
Building on OSSE development with AIST-18-0041

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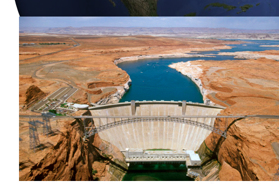
Actual or Potential Infusions and Collaborations

- SnowModel has been (and continues to be) used in SnowEx Alaska field campaign planning activities
  - Snow modelling ensemble project includes LIS-SnowModel
  - SnowModel is the most accurate of the model simulations in Alaska
  - SnowModel is also the most independent (least similar) to the other models
- LIS-SnowModel is going to be used in multiple NASA projects :
  - Terrestrial Hydrology Program
    - PI: James McCreight
    - PI: Nicoleta Cristea
  - Interdisciplinary Sciences
    - PI: Jessica Lundquist
  - Water Resource Applications (Proposed)
    - PI: Nicoleta Cristea
- NSF-funded “SOS: Sublimation of Snow” project will provide updates to snow sublimation parameterizations and can be integrated with SnowModel
- Opportunity to provide high-resolution SnowModel simulations over the East River basin for DOE funded SAIL field campaign and NOAA funded SPLASH campaign
- Bureau of Reclamation is hosting a “SWE Prize Competition”
  - PI-Gutmann and Co-I Vuyovich have helped in the formulation
- The Bureau of Reclamation is working under the Snow Water Supply Forecasting Act we have engaged in discussions to use LIS-SnowModel for DA



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Publications and Presentations

Reynolds, D. and J. D. Lundquist, 2020: Evaluating Wind Fields for Use in Basin-Scale Distributed Snow Models, *Water Resources Research.* doi:10.1029/2020WR028536.

Kim, R. S., et al. 2021: Snow Ensemble Uncertainty Project (SEUP): Quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling, The Cryosphere, doi:10.5194/tc-15-771-2021.

Wrzesien et al, 2022: Development of a “nature run” for observing system simulation experiments (OSSE) for snow mission development. *Journal of Hydrometeorology*. Accepted

2021 Presentations

Wrzesien et al, 2021: Evaluation of a Calibrated “Nature Run” for Observation System Simulation Experiments (OSSE) against Snow Depth Observations. AMS Annual meeting January, 2021

Kim et al, 2021: Impact evaluation of snow water equivalent uncertainty on streamflow estimation across North America using ensemble land surface modeling. AMS Annual meeting January, 2021

Gutmann et al, 2021: Explicitly Simulating Snow Spatial Variability at Scale to Improve Predictions. AMS Annual meeting January, 2021

Gutmann et al, 2021: SY12B-06: High-resolution snow modeling and data assimilation techniques for the next generation of remotely sensed observations on a snow covered digital twin. AGU Fall Meeting.

Arsenault et al, 2021: C35G-0945: Implementing SnowModel into the Land Information System Framework to Support High Resolution Modeling of Snow Heterogeneity. AGU Fall Meeting

Wrzesien et al, 2021: H52A-01: Modeled snow intercomparison over Fairbanks, Alaska domain: spatial and interannual variability from Land Information System simulations. AGU Fall Meeting

Mower et al., 2021: H54G-02: High performance computing for high-resolution snow modeling. AGU Fall Meeting

List of Acronyms

- ASO Airborne Snow Observatory
- HRRR High Resolution Rapid Refresh model
- CDEC California Data Exchange Center (in situ sites)
- MM MicroMet
- WN Wind Ninja
- DEM Digital Elevation Model
- DS Decadal Survey
- km Kilometer
- SEUP Snow Ensemble Uncertainty Project
- LIS Land Information System
- LDT Land Data Toolkit
- LVT Land Verification Toolkit
- LISF LIS Framework (LIS+LDT+LVT)
- SWE Snow Water Equivalent
- SWS Snow Water Storage
- SCF Snow Cover Fraction
- GDAS Global Data Assimilation System
- NLDAS National Land Data Assimilation System
- MERRA Modern-Era Retrospective Analysis for Research and Applications
- ECMWF European Center for Medium Range Weather Forecasting
- CV Coefficient of Variation
- OSSE Observing System Simulation Experiment
- DA Data Assimilation
- EnKF Ensemble Kalman Filter
- OI Optimal Interpolation
- SM SnowModel
- NMP NoahMP
- CR Crocus
- LSM Land Surface Model
- NCAR National Center for Atmospheric Research
- GSFC Goddard Space Flight Center
- UW University of Washington
- CSU Colorado State University
- UMD University of Maryland

Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals

Prof. Bart Forman (PI, UMD)
Dr. Sujay Kumar (Co-I, GSFC)
Dr. Paul Grogan (Co-I, Stevens Institute)
Dr. Rhae Sung Kim (Co-I, GSFC)
Dr. Yeosang Yoon (Co-I, GSFC)
Dr. Yonghwan Kwon (Co-I, GSFC)
Lizhao Wang (UMD)
Alireza Moghaddasi (UMD)
Colin McLaughlin (UMD)

AIST-18-0041 Annual Technical Review
January 7, 2022

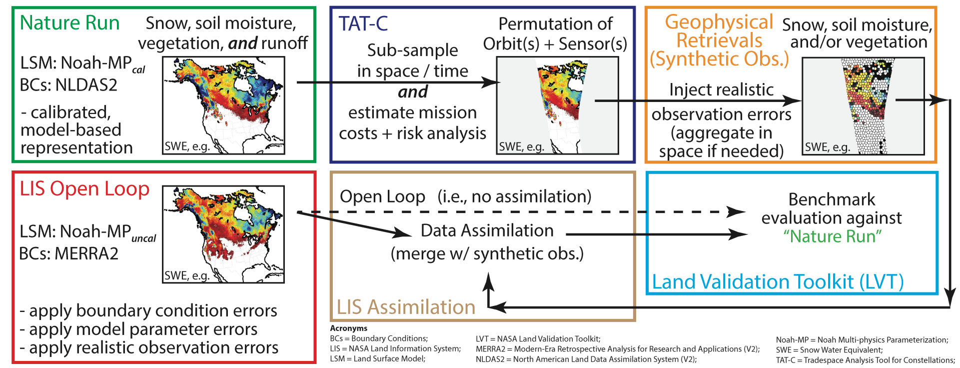
Teams:
University of Maryland
NASA Goddard Space Flight Center
Stevens Institute of Technology

Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals

PI: Barton A. Forman, University of Maryland

Objective

- Create a mission planning tool to help inform experimental design with **relevance to global snow, soil moisture, and vegetation** in the terrestrial environment
- Use the extensive sensor simulation, orbital configuration, data assimilation, optimization, uncertainty estimation, cost estimation, and risk assessment tools in **LIS and TAT-C** to harness the information content of Earth science mission data
- Technologies include **passive and active microwave remote sensing, optical remote sensing, LiDAR**, hydrologic modeling, orbital emulators, adaptive sensor viewing, and data assimilation



Approach:

- Develop a **coupled snow-soil moisture-vegetation observing system simulation experiment (OSSE)** extending the capabilities of LIS and TAT-C
- Conduct end-to-end OSSEs to investigate the impact of **new and future mission concepts** on LIS model efficacy, including the impact of adaptive versus fixed viewing of space-borne sensors
- Conduct end-to-end OSSEs to characterize tradeoffs in spatiotemporal resolutions and orbital configurations (constellations), including mission cost estimates and risk assessments

Key Milestones (start date 01 Jan 2020)

• Data collection and preprocessing	03/20
• Develop Nature Run	06/20
• Develop Geophysical Observation Operators	09/20
• Fixed, Single-sensor DA Experiments	01/21
• Develop Adaptive Sensor Viewing Operator	01/21
• Adaptive, Single-sensor DA Experiments	06/21
• Fixed, Multi-sensor DA Experiments	09/21
• Adaptive, Multi-sensor DA Experiments	12/21
• Project Reporting	Quarterly

TRL_{in} = 3 **TRL_{out} = 6**

CoIs: Sujay Kumar, GSFC; Paul Grogan, Stevens Inst.; Rhae Sung Kim, GSFC; Yonghwan Kwon, GSFC; Yeosang Yoon, GSFC;

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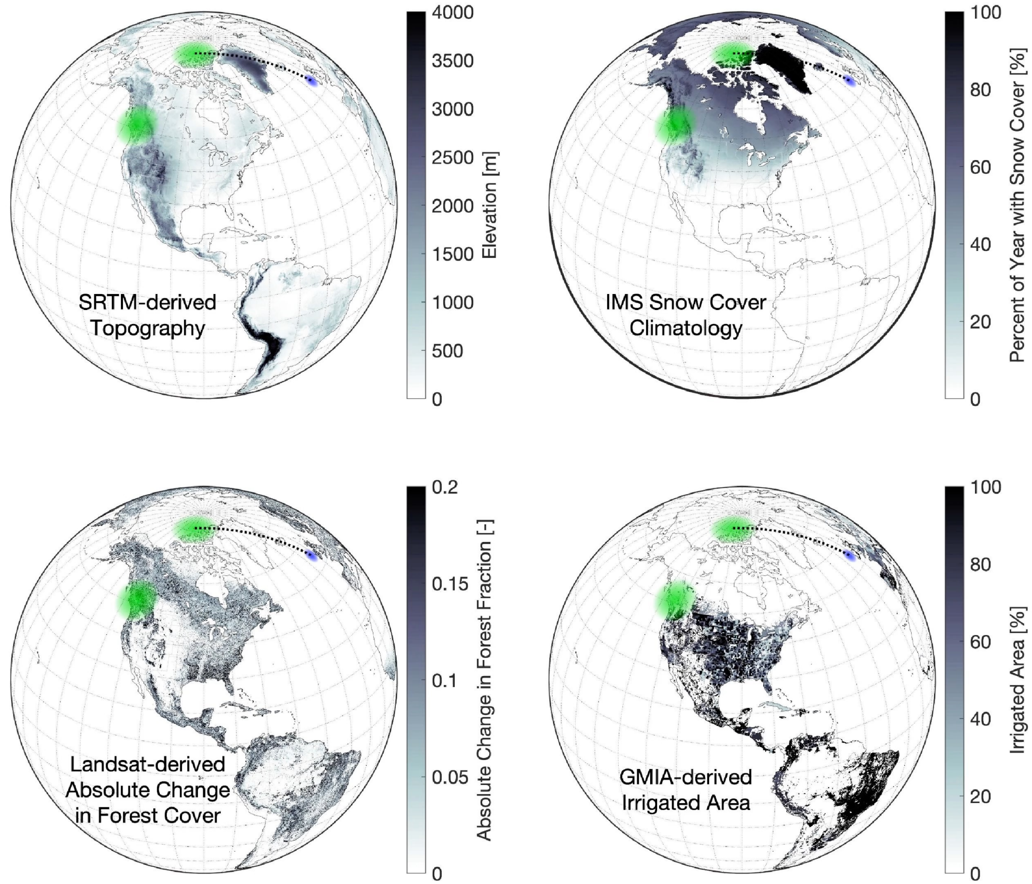
Coupled Snow-Soil Moisture-Vegetation Processes

Investigate "optimal" coupled snow-soil moisture-vegetation observing system (integrated, cohesive response)

Background and Objectives

- Terrestrial freshwater is a **highly dynamic, coupled** system
  - Requires a **cohesive, physically-consistent** framework
- Leverage suite of remotely-sensed observations
  - **LIDAR** → snow and vegetation information
  - **Passive MW** → snow and soil moisture information
  - **Active MW** → snow, soil moisture, and vegetation information
  - **VIS / NIR** → snow and vegetation information
- Need for observing system simulation experiment (OSSE) to study complex interplay of synergistic effects
  - Use in **data assimilation** framework to **improve coupled snow-soil moisture-vegetation** response

Coordination of Space-borne Sensors

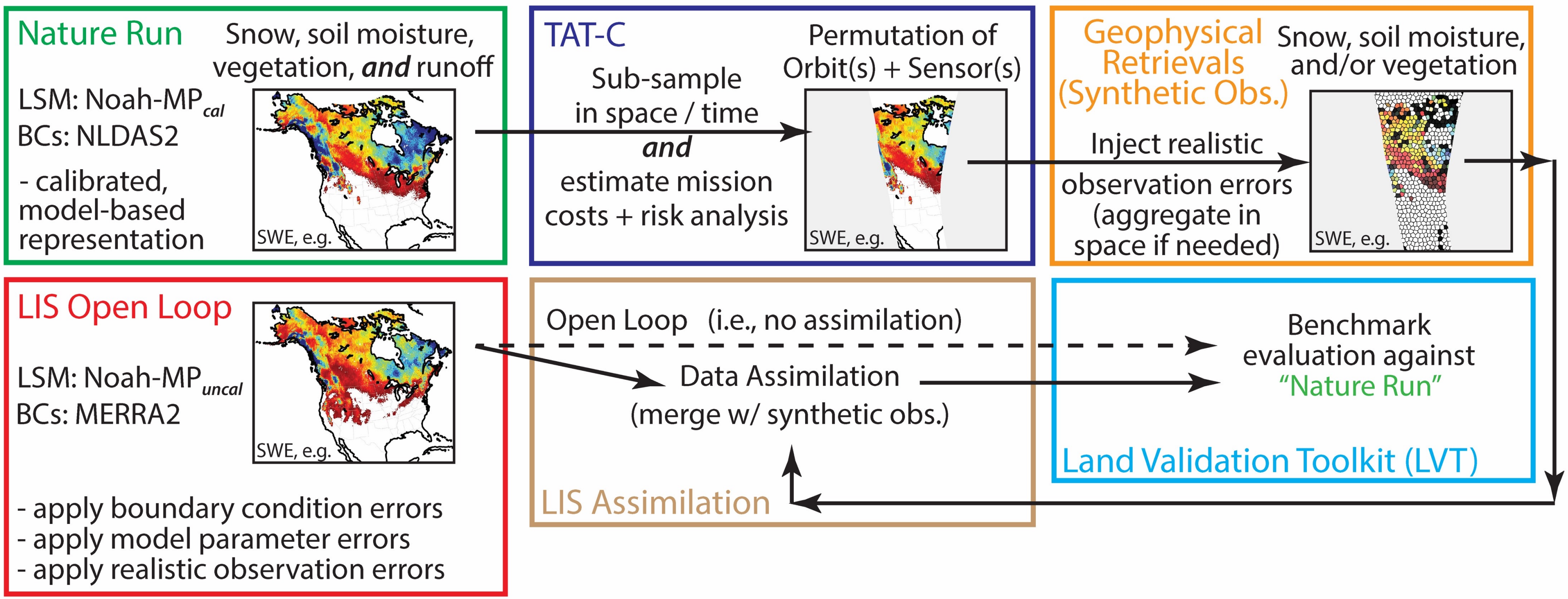


= Passive Microwave Radiometer (snow; soil moisture)

= Synthetic Aperture RADAR (snow condition; soil moisture; vegetation)

= Optical LiDAR (snow depth; vegetation)

Technical Development Overview -- OSSE



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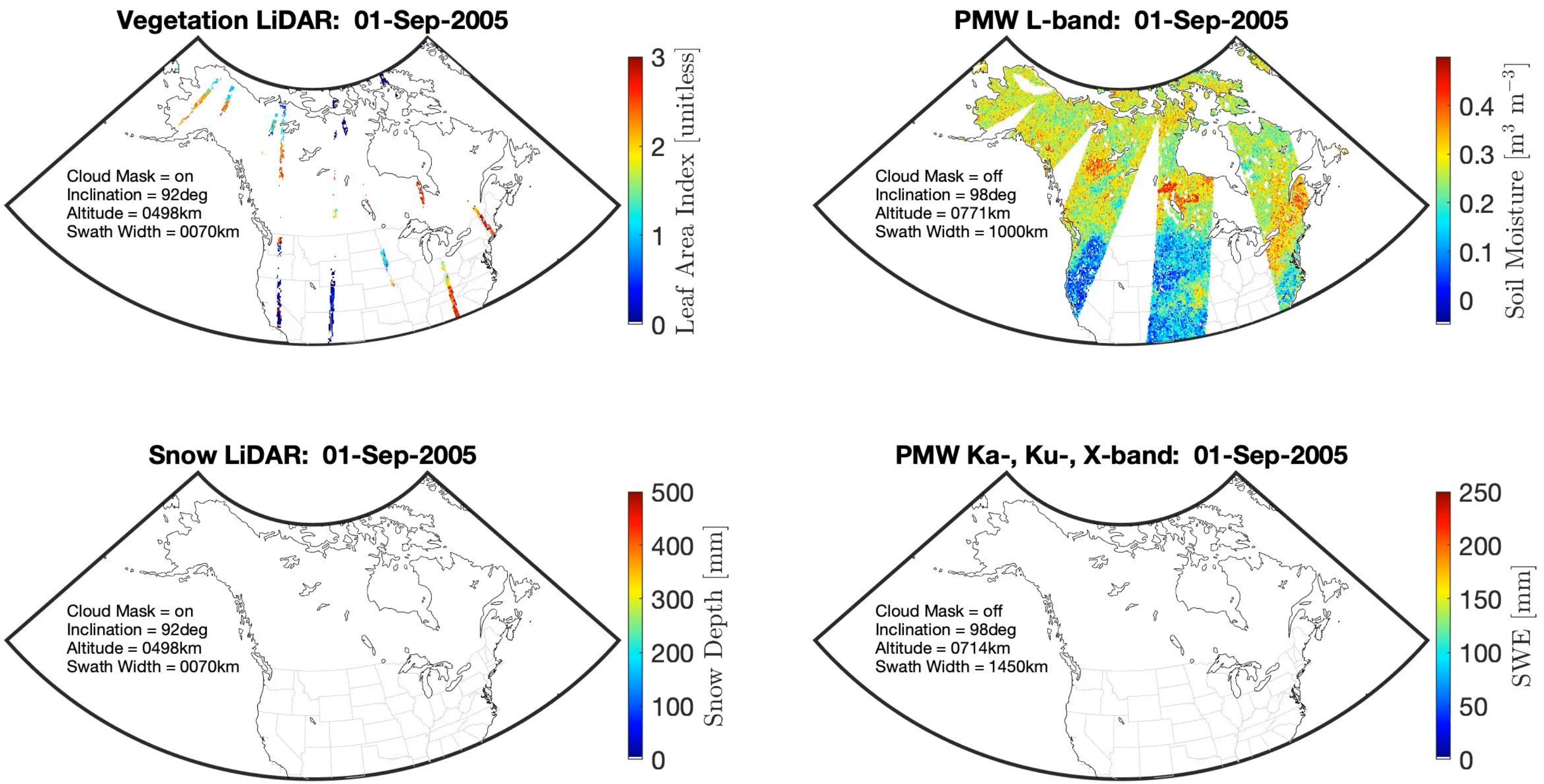
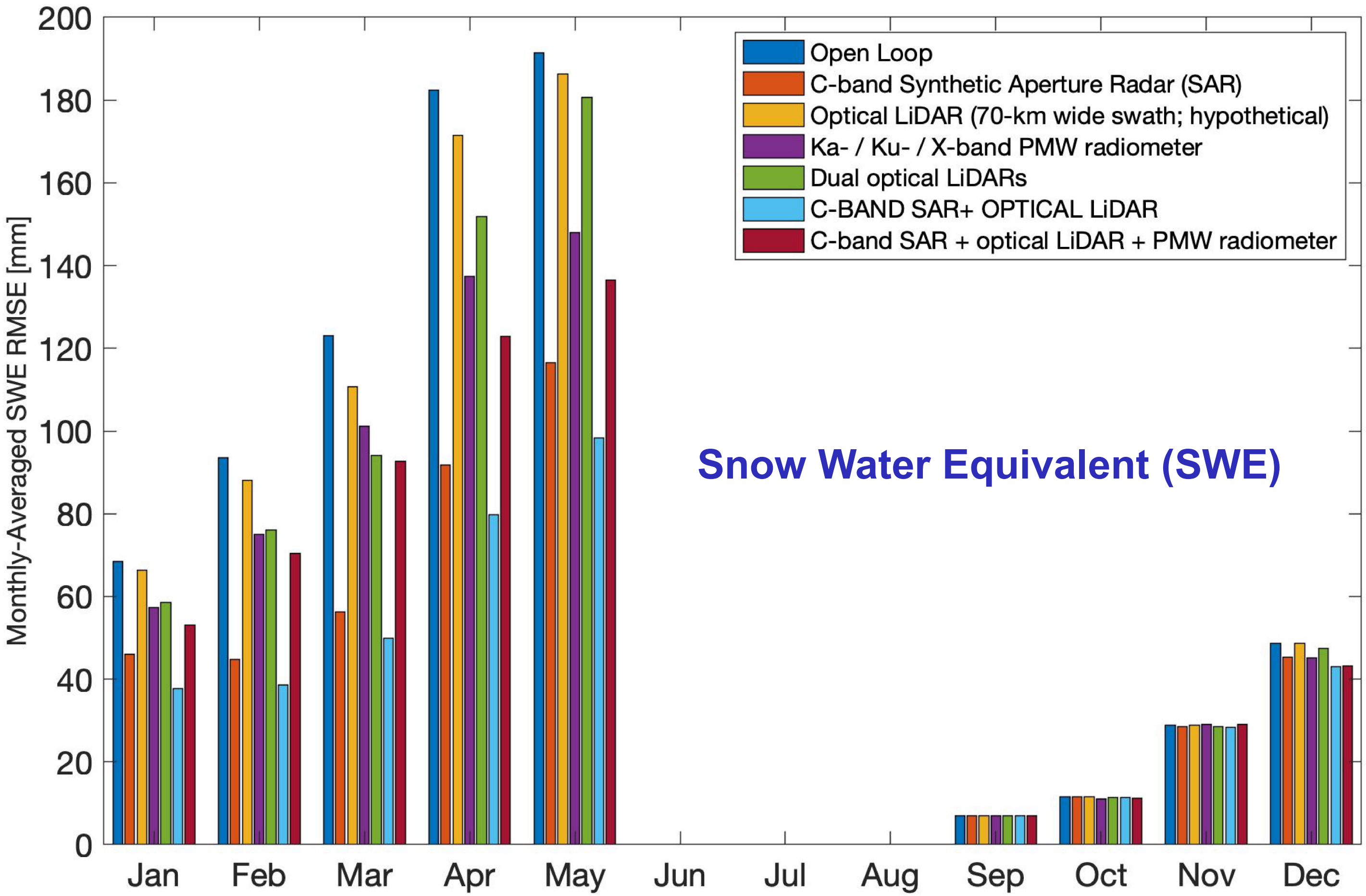
Nature Run and Synthetic Retrievals



Synthetic retrievals derived from **Nature Run** (Wrzesien et al., *Accepted*)

Wrzesien, M. L., S. Kumar, C. Vuyovich, E. D. Gutmann, R. S. Kim, B. A. Forman, M. Durand, M. Raleigh, R. Webb, and P. Houser. ``Development of a `nature run' for observing system simulation experiments (OSSE) for snow mission development", *Journal of Hydrometeorology*, Accepted.

Subset of Multi-Sensor Assimilation Results



Figures courtesy of Alireza Moghaddasi (Ph.D. student @ UMD)

Subset of Multi-Sensor Assimilation Results

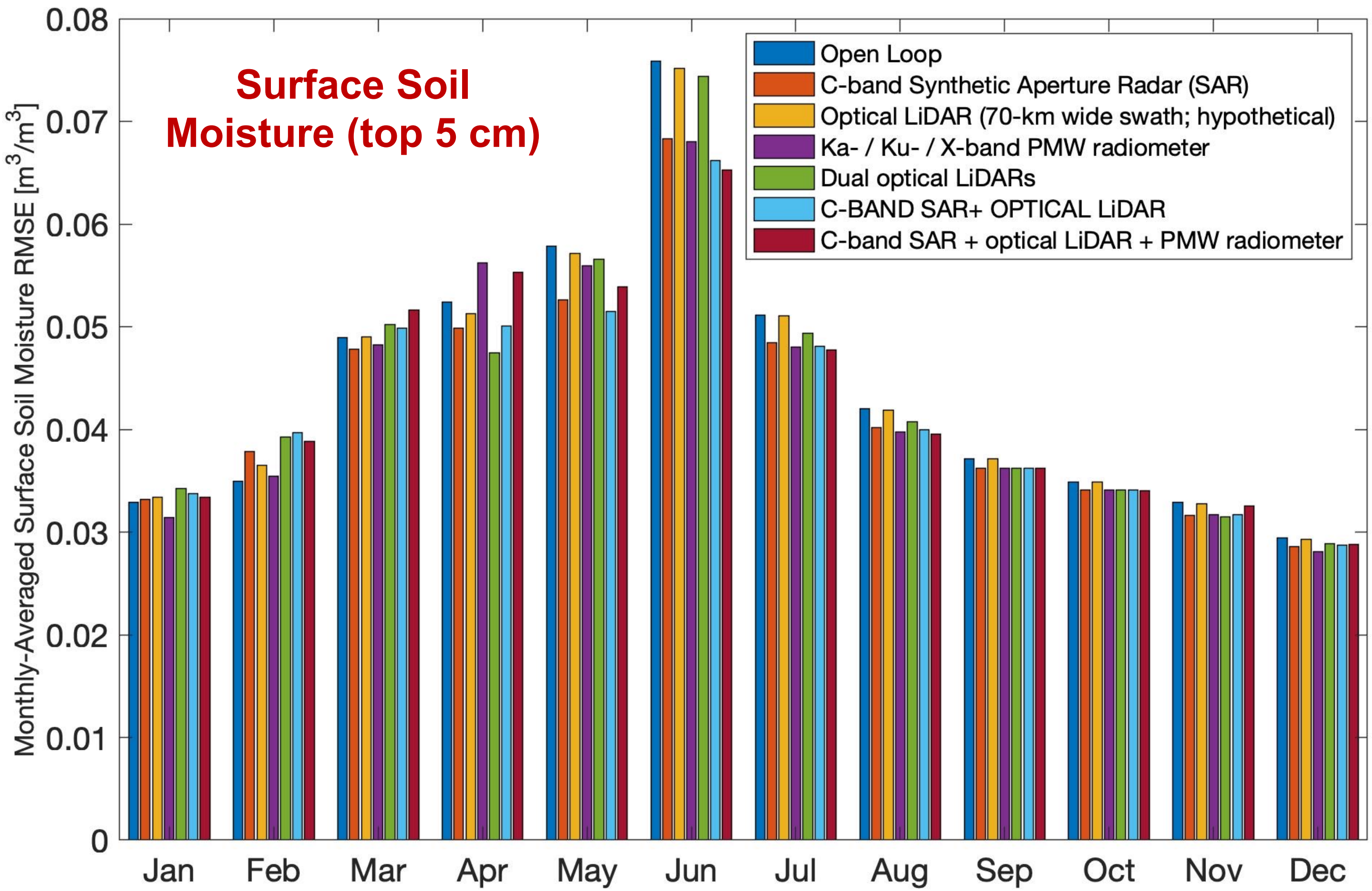


Figure courtesy of Alireza Moghaddasi (Ph.D. student @ UMD)

Subset of Multi-Sensor Assimilation Results

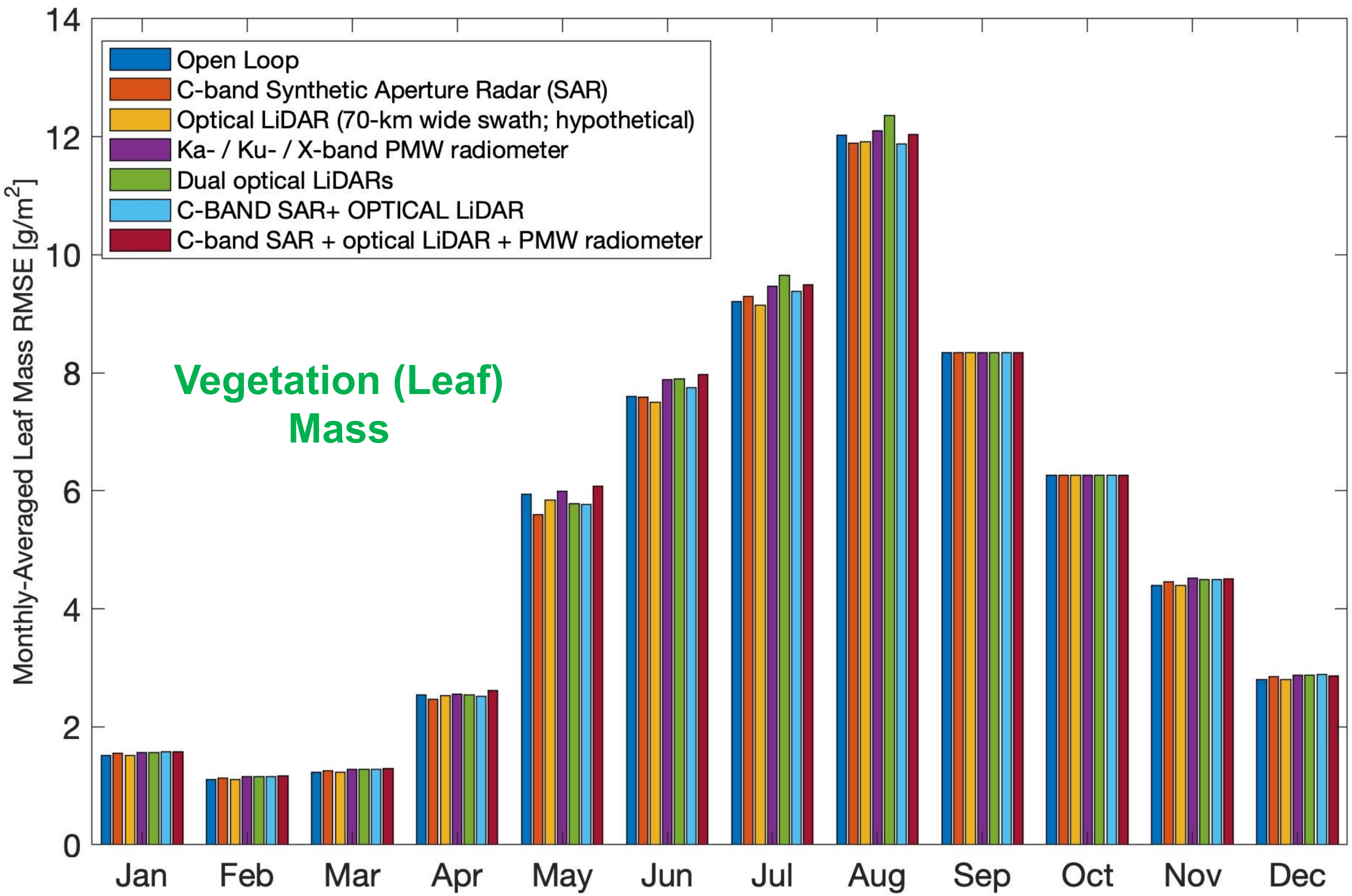


Figure courtesy of Alireza Moghaddasi (Ph.D. student @ UMD)

Subset of Multi-Sensor Assimilation Results

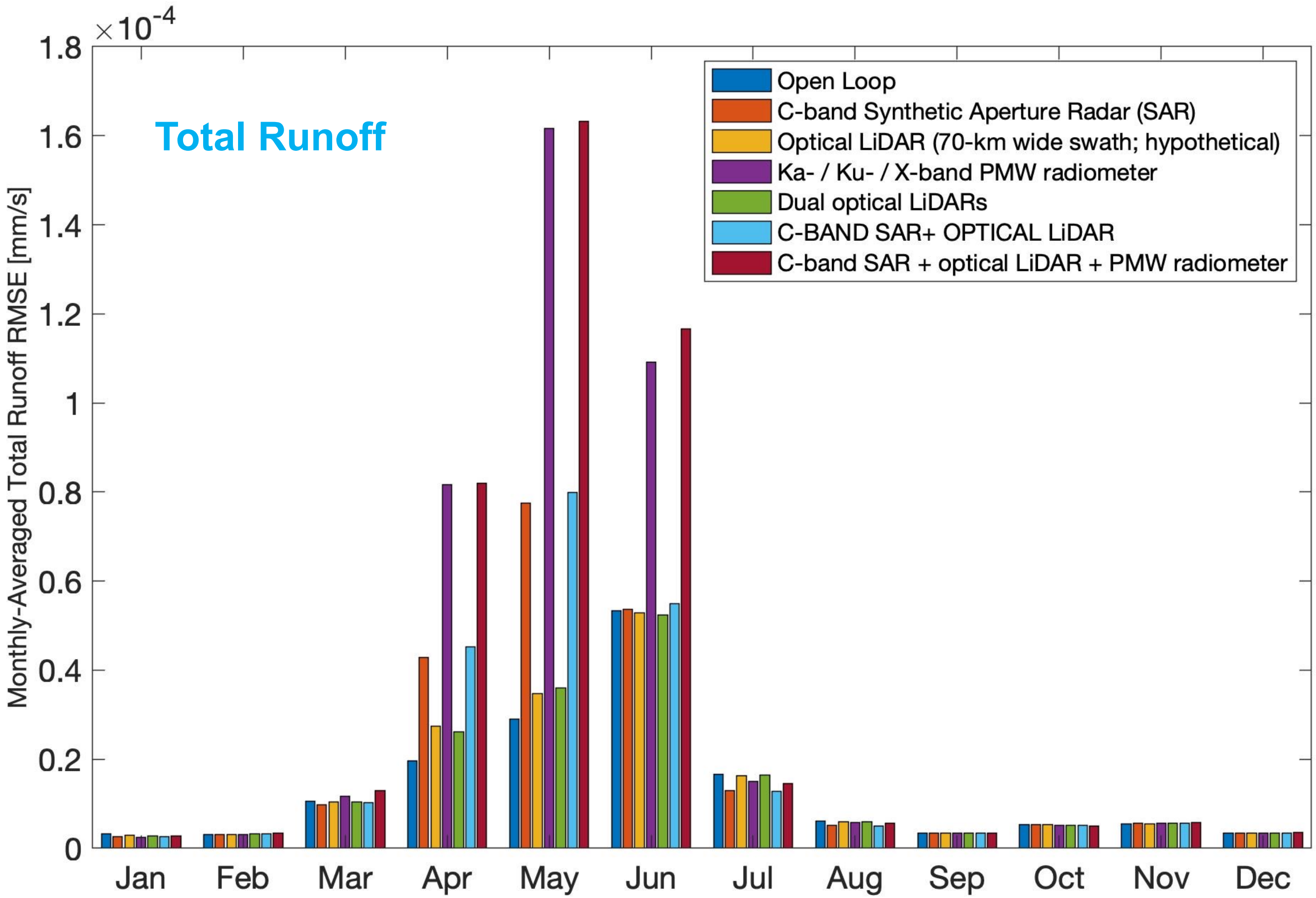


Figure courtesy of Alireza Moghaddasi (Ph.D. student @ UMD)

Limits to C-band SAR Retrieval Errors

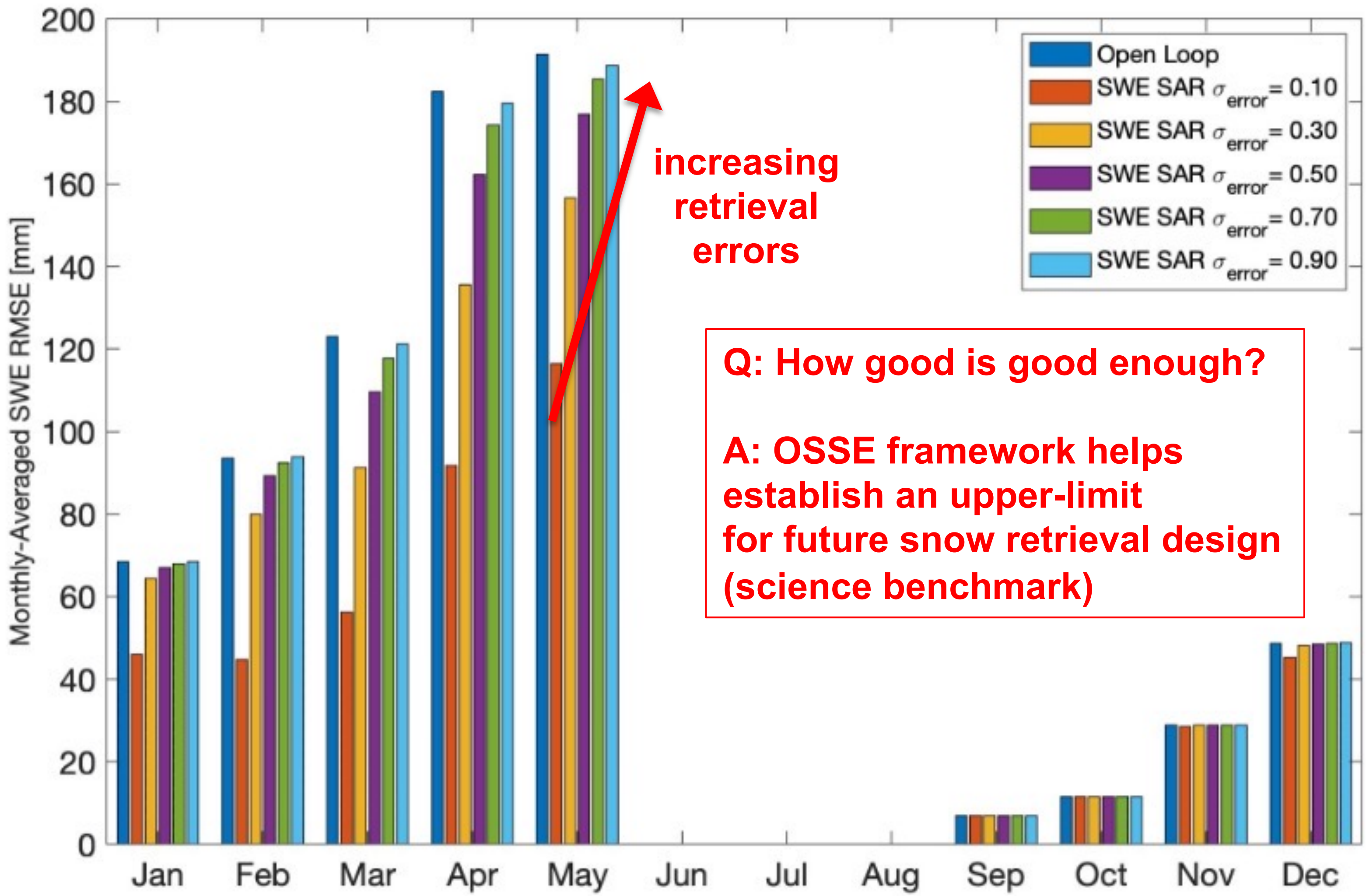
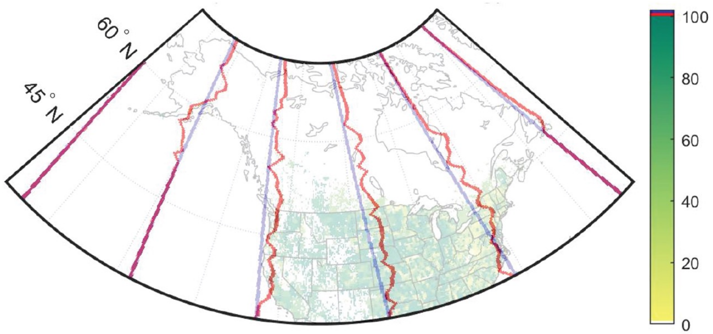


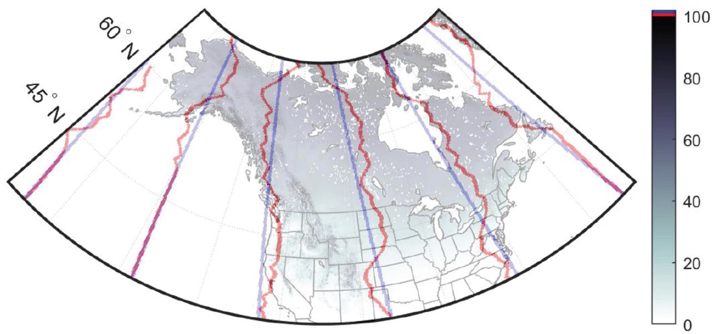
Figure courtesy of Alireza Moghaddasi (Ph.D. student @ UMD)

Adaptive Viewing Component

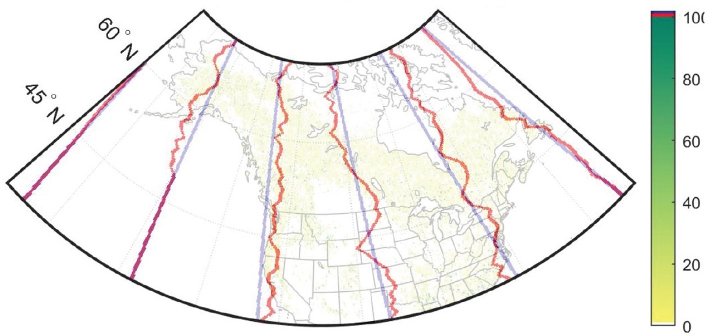
Percent Irrigated Areas
146% increase in viewed target (relative to static viewing)



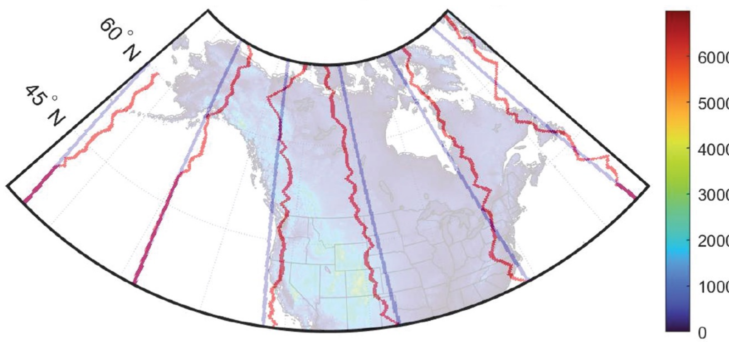
Snow Cover Climatology
161% increase in viewed target (relative to static viewing)



Change in Forest Cover Percentage
126% increase in viewed target (relative to static viewing)



Land Surface Elevation
107% increase in viewed target (relative to static viewing)



Static viewing path shown in blue
Adaptive viewing path shown in red

NOTE: paths shown here only a single realization from a probabilitic ensemble of realizations

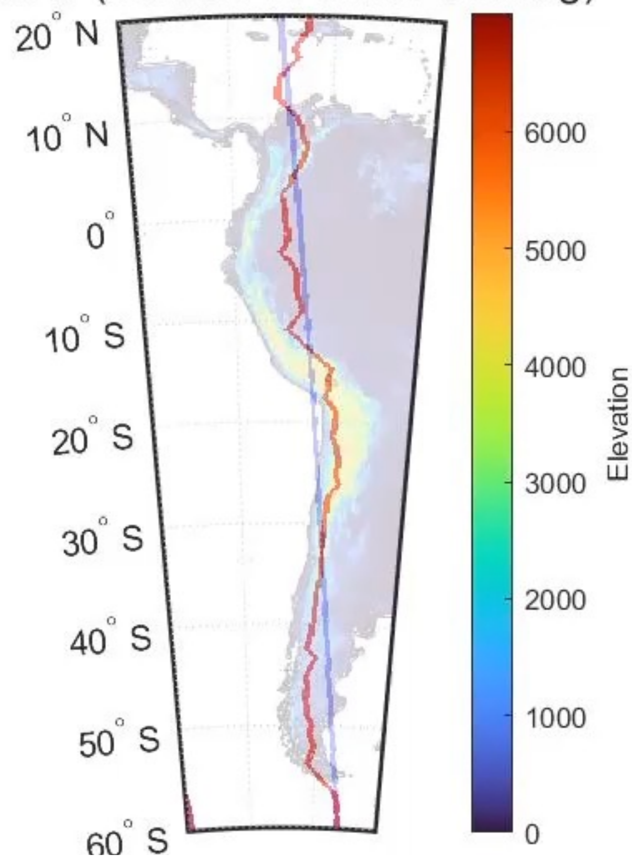
Figure courtesy of Colin McLaughlin (Master's student @ UMD)

Adaptive Viewing Component

Take-Home Point:
Adaptive Viewing (red swath) sees more snow and ice, e.g., relative to **Static Viewing (blue swath)**

Simulation Parameters	
Surface Target	Shuttle Radar Topography Mission (STRM) Land Surface Elevation
Study Domain	South America
Max. Slew Angle	30 [deg]
Max. Slew Angle Rate	1.0 [deg/s]
Swath Width	40 [km]
Inclination Angle	92 [deg]
Altitude	498 [km]

Improvement in Surface Target Viewed
110% (relative to static viewing)



Video courtesy of Colin McLaughlin (Master's student @ UMD)

A Singular Metric: In Search of the One

Weighted as a Function of Hydrologic State

$$\boxed{NIC_{RMSE,weighted} = \alpha \cdot NIC_{RMSE,snow} + \beta\, NIC_{RMSE,soil\ moisture} + \gamma\, NIC_{RMSE,vegetation} + \delta\, NIC_{RMSE,runoff}}$$

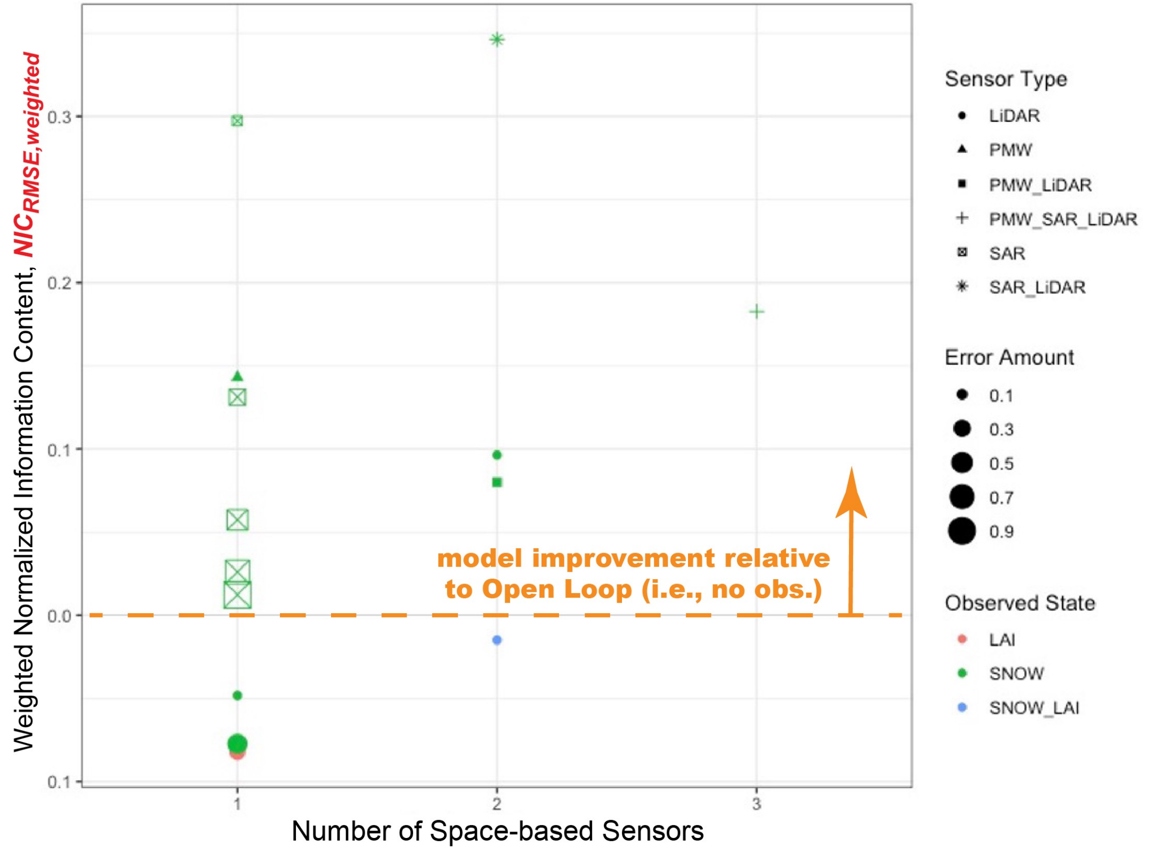


Figure courtesy of Alireza Moghaddasi (Ph.D. student @ UMD)

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Summary of Accomplishments and Future Plans

- **Nature Run** completed
- **Open Loop** completed
- **Univariate** assimilation experiments → **complete**
- **Multivariate** assimilation experiments → **on-going**
- Exploration of retrieval **error characterization**
- Integration **adaptive viewing vs. static viewing** into OSSE
- Singular, **cohesive framework** to assess integrated hydrologic response
- OSSE amenable to suite of **terrestrial hydrology** applications

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Actual or Potential Infusions and Collaborations

- Terrestrial Hydrology Program (**THP**)
- Modeling Analysis and Prediction (**MAP**)
- New Observing Strategies (**NOS-L**)
- NASA Snow Experiment (**SnowEx**) activities
- Snow Ensemble Uncertainty Project (**SEUP**)
- Mass change And Geosciences International Constellation (**MAGIC**)

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Publications

Conference Presentations

Wrzesien, M. L., S. V. Kumar, C. Vuyovich, E. D. Gutmann, R. S. Kim, B. A. Forman, M. Durand, M. Raleigh, R. Webb, and P. Houser. *Evaluation of a calibrated ``nature run" for observation system simulation experiments (OSSE) against snow depth observations*, American Meteorological Society Annual Meeting, New Orleans, Louisiana, United States, 2021.

Kwon, Y., Y. Yoon, S. V. Kumar, B. A. Forman, and L. Wang*. *Quantifying the observational requirements of a space-borne LiDAR snow mission*, Asia Oceania Geosciences Society Annual Meeting, Singapore, 2021.

McLaughlin, C. P.*, B. A. Forman, and L. Wang*. Towards the incorporation of adaptive viewing in observing system simulation experiments (OSSEs) to preferentially view snow-covered terrain, 77th Eastern Snow Conference, Saskatoon, Saskatchewan, Canada, 2021.

Wang, L.*, B. A. Forman, S. V. Kumar, Y. Kwon, P. Grogan, R. S. Kim, M. L. Wrzesien, and Y. Yoon. On the complementary value of space-based snow observations for snow mass estimation within an observing simulation system experiment, 77th Eastern Snow Conference, Saskatoon, Saskatchewan, Canada, 2021.

Moghaddasi, A.*, L. Wang*, B. A. Forman, and S. V. Kumar. Impact of passive microwave radiometry and LiDAR assimilation on hydrologic cycle estimation, 77th Eastern Snow Conference, Saskatoon, Saskatchewan, Canada, 2021.

McLaughlin, C.*, B. A. Forman, and L. Wang*. Leveraging adaptive viewing to improve the efficacy of space-borne retrievals for terrestrial hydrology applications within an observing system simulation experiment (OSSE), American Geophysical Union Annual Meeting, New Orleans, Louisiana, United States, 2021.

* = Graduate Student Advisee

Publications (continued)

Journal Articles

Kim, R. S., S. V. Kumar, C. Vuyovich, P. Houser, J. Lundquist, L. Mudryk, M. Durand, A. Barros, E. J. Kim, B. A. Forman, E. D. Gutman, M. Wrzesien, C. Garnaud, M. Sandells, H.-P. Marshall, N. Cristea, J. Pflug, J. Johnston, Y. Cao, D. Mocko, S. Wang. ``Snow Ensemble Uncertainty Project (SEUP): Quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling", *The Cyrosphere*, doi:10.5194/tc-15-771-2021, 2021.

Kwon, Y., Y. Yoon, B. A. Forman, S. V. Kumar, and L. Wang*, Quantifying the observational requirements of a space-borne LiDAR snow mission, *Journal of Hydrology*, doi.org/10.1016/j.jhydrol.2021.126709, 2021.

Park, J.*, B. A. Forman, and S. V. Kumar. ``Estimation of snow mass information via assimiltion of C-band synthetic aperture radar backscatter observations into an advanced land surface model" *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, doi:10.1109/JSTARS.2021.3133513, 2021.

Wang, L.*, B. A. Forman, and E. Kim. ``Exploring the spatiotemporal coverage of terrestrial snow mass using a suite of satellite constellation configurations", *Remote Sensing*, Minor Revisions.

Wrzesien, M. L., S. Kumar, C. Vuyovich, E. D. Gutmann, R. S. Kim, B. A. Forman, M. Durand, M. Raleigh, R. Webb, and P. Houser. ``Development of a `nature run' for observing system simulation experiments (OSSE) for snow mission development", *Journal of Hydrometeorology*, Accepted.

Ph.D. Dissertation

Wang, L.* (expected in June 2022). *Combining Hyperspectral, Passive Microwave, and Synthetic Aperture Radar to Improve Terrestrial Freshwater Characterization*. University of Maryland.

Master's Thesis

McLaughlin, C.* (expected in May 2022). *Optimization of Adaptive Remote Sensing for Use in an Observing System Simulation Experiment of Terrestrial Freshwater*. University of Maryland.

* = Graduate Student Advisee

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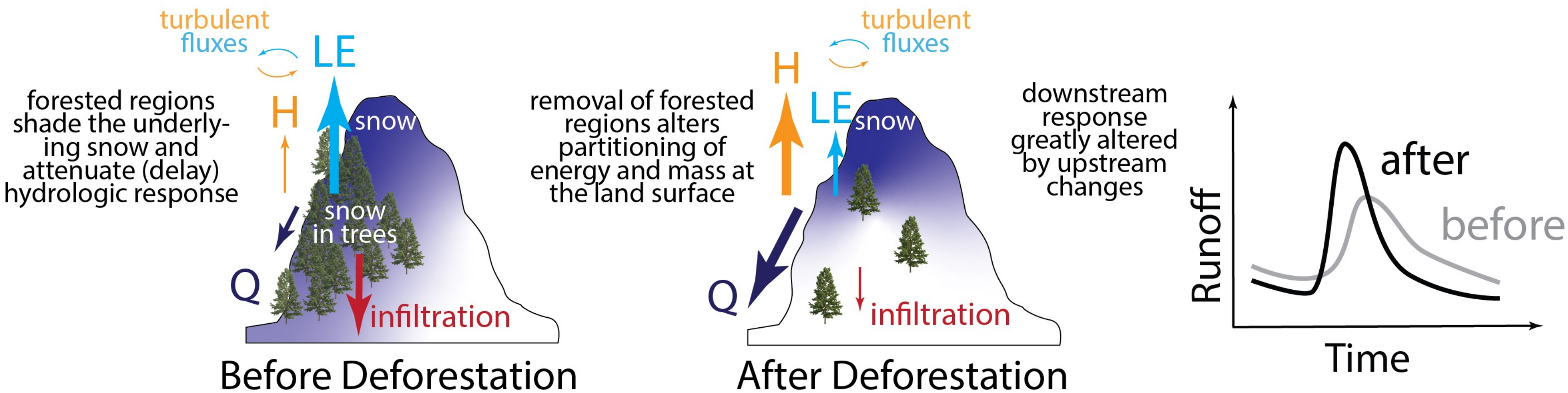
Acronyms

List of Acronyms

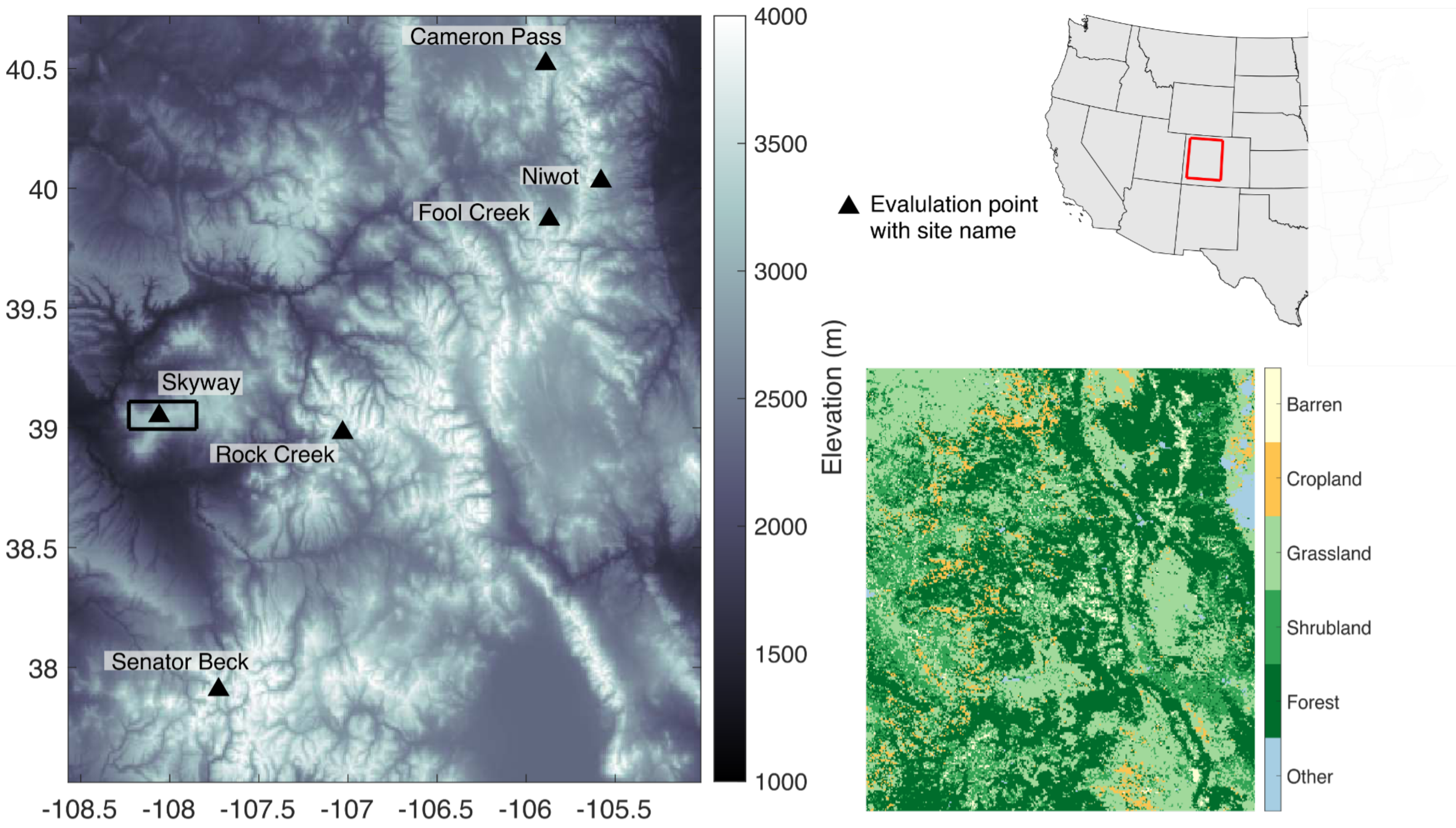
• AMSR-E	Advanced Microwave Scanning Radiometer
• DA	Data Assimilation
• ICESat-2	Ice, Cloud, and land Elevation Satellite-2
• LiDAR	Light Detection and Ranging
• LIS	Land Information System
• MAP	Modeling, Analysis, and Prediction
• NIR	Near Infrared
• OL	Open Loop
• OSSE	Observing System Simulation Experiment
• PMW	Passive Microwave
• RADAR	Radio Detection and Ranging
• SAR	Synthetic Aperture RADAR
• SMAP	Soil Moisture Active Passive
• TAT-C	Trade-space Analysis Tool – Constellations
• THP	Terrestrial Hydrology Program
• VIS	Visible

Extra Slides

Coupled Snow-Soil Moisture-Vegetation System



Study Domain



Wrzesien et al., Accepted, *Journal of Hydrometeorology*

Normalized Information Content, *NIC*

Normalized Information Content (NIC)

$$NIC_{RMSE} = \frac{RMSE_{OL} - RMSE_{DA}}{RMSE_{OL}}$$

$NIC \in [-\infty \quad 1]$

$NIC > 0$ denotes improvement over OL

Weighted by Hydrologic State

$$NIC_{RMSE,weighted} = \alpha \cdot NIC_{RMSE,snow} + \beta\ NIC_{RMSE,soil\ moisture} + \gamma\ NIC_{RMSE,vegetation} + \delta\ NIC_{RMSE,runoff}$$

A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design

Derek J. Posselt (PI, JPL)
Brian Wilson (Co-I, JPL)

AIST-18-0009 24 Month Review
07 January 2022

Team listing:
Rachel Storer, UCLA / Derek Tropf, JPL / Vishal Lall, JPL
Amir Forouzani, JPL / George Duffy, JPL / Matt Lebsock, JPL
Simone Tanelli, JPL / Noppasin Niamsuwan, JPL

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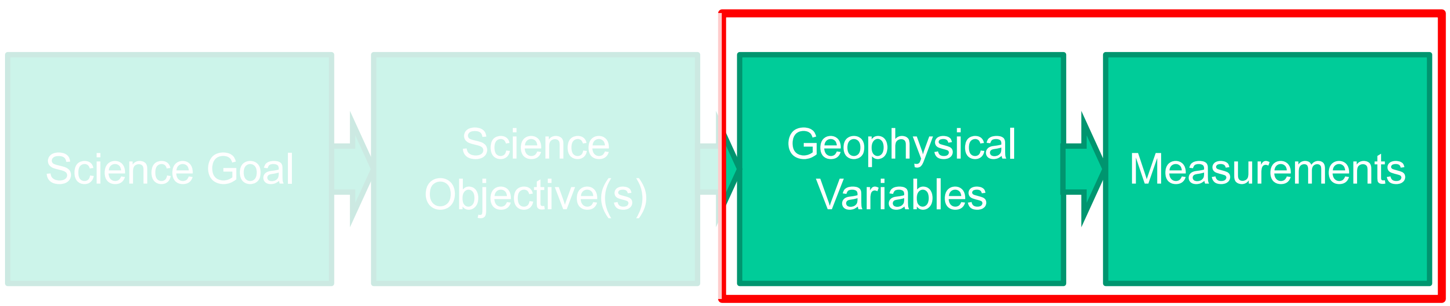
Scientific Challenge

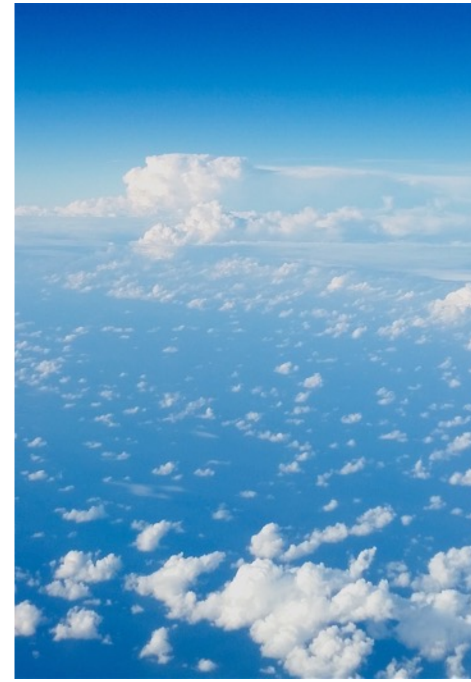
- Clouds and precipitation are central to climate and weather
- After decades of space-borne measurements,
  key processes are still missing
- Goal: design a new observing system (e.g. AOS/ACCP*)
  - Address specific science objectives
  - Consider the vast array of possible measurements
  - Rigorously quantify uncertainties



*Atmosphere Observing System
https://vac.gsfc.nasa.gov/accp/home.htm

Technical Challenge

- The design trade-space is *large* and clouds are *diverse*
- Dimensionality of the mission design problem is *immense*
  - Multiple different geophysical scenarios (different cloud types)
  - Diversity of measurement types (active, passive, single-point, distributed)
  - Multiple sources of uncertainty (instrument noise, forward models, sampling characteristics)
- **Computational challenge: identify suitable candidates**



For each geophysical variable → For each cloud type → For each combination of measurements → Considering all sources of uncertainty → Determine whether measurements meet mission requirements

Solution: Accelerate OSSEs
Parallel OSSE Toolkit – Mission Design

Brian Wilson – System Architect

OSSE Components

Nature Runs
Large Eddy Simulations
Cloud Resolving Models
Global Simulations

Instrument Simulation
Radar
Passive Microwave
(Extensible via pluggable containers)

Bayesian Retrievals
Optimal Estimation
Ensemble Kalman Filter
Markov chain Monte Carlo

ParMAP: Flexible Parallelism

Standalone Workstation

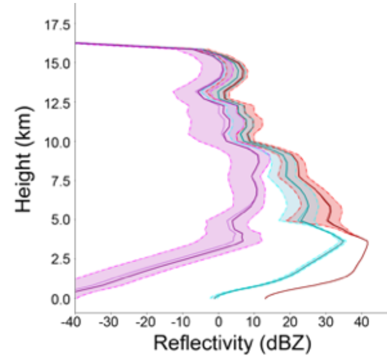
Clusters and HPC

Cloud Computing

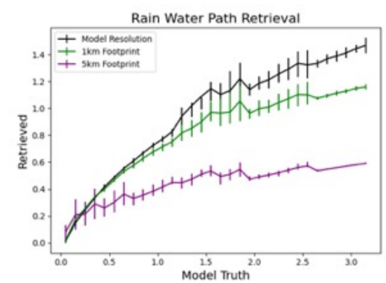
aws

Uncertainty Analysis

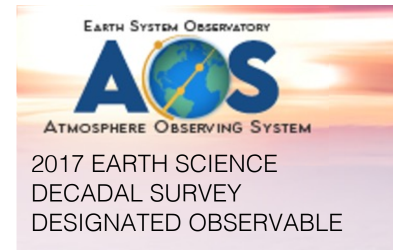
Measurement Uncertainty



Geophysical Variable Uncertainty



Mission Design Decisions



ESTO Earth Science Technology Office

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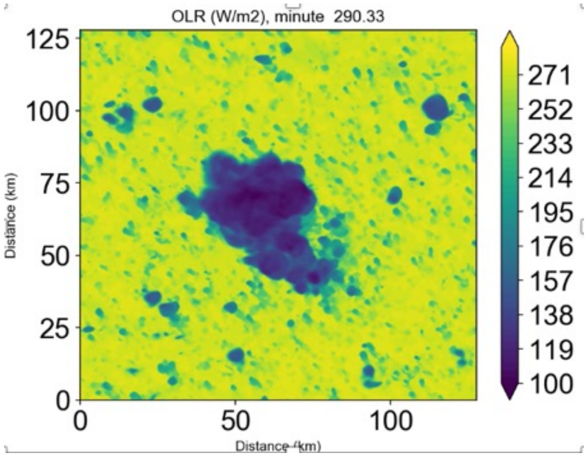
Example 1: Uncertainty Inherent in Clouds
AOS (ACCP) Objective 3 – Deep Convection

Experiment Configuration:
- 750 input model profiles
- 3 radar frequencies (Ku, Ka, W)
- 5 uncertain parameters, 500 total possible values
- 750 x 3 x 500 = 1,125,000 forward model runs

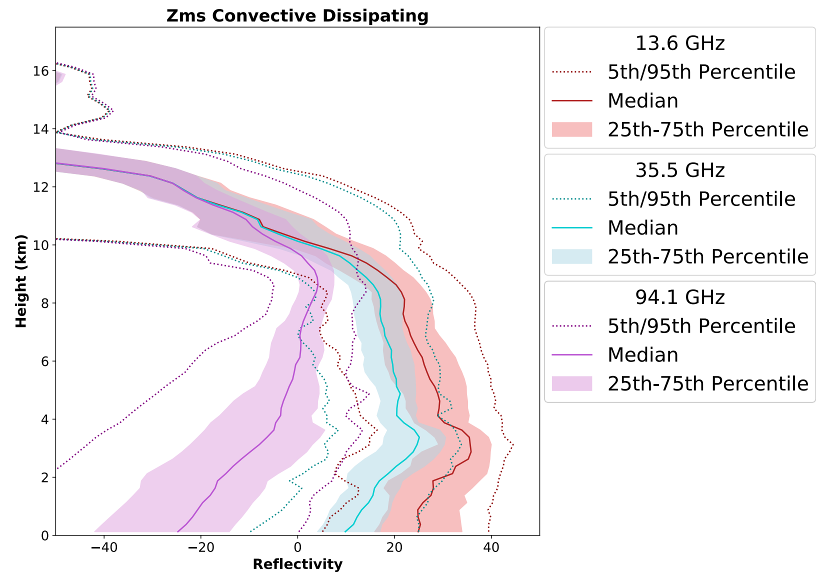
Inputs:
- Nature run profiles
- Range of uncertainty

Outputs:
- Ensemble of possible radar profiles for each input model profile and frequency
- Improved understanding of uncertainty in radar observations of convection



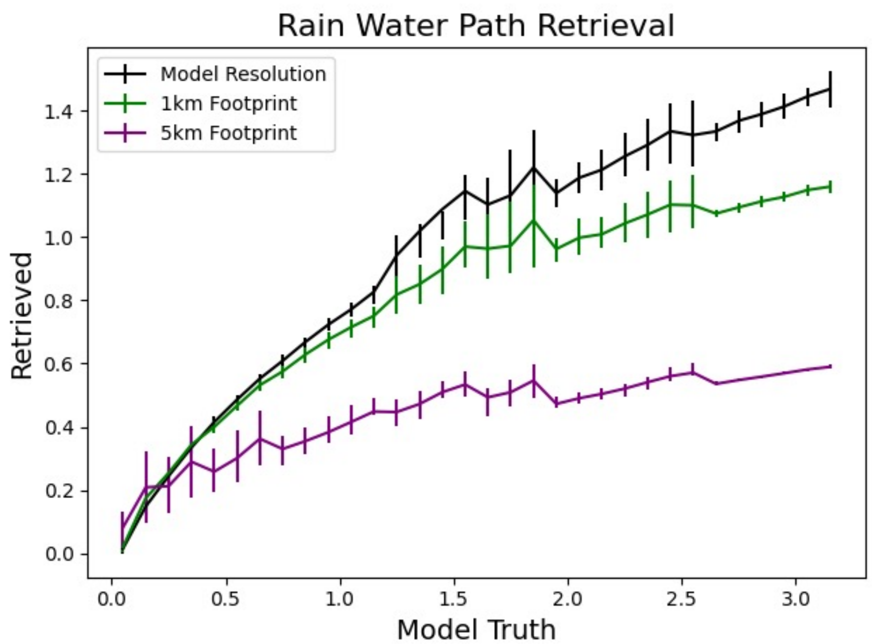
~10^6 Forward Model Runs

3600+ minutes sequential
120 minutes parallel
(40 cores) 36x speedup
20 minutes AWS Lambdas
(1000 Lambda Workers)



Example 2: Shallow Cloud Rain Retrieval (ACCP O1)

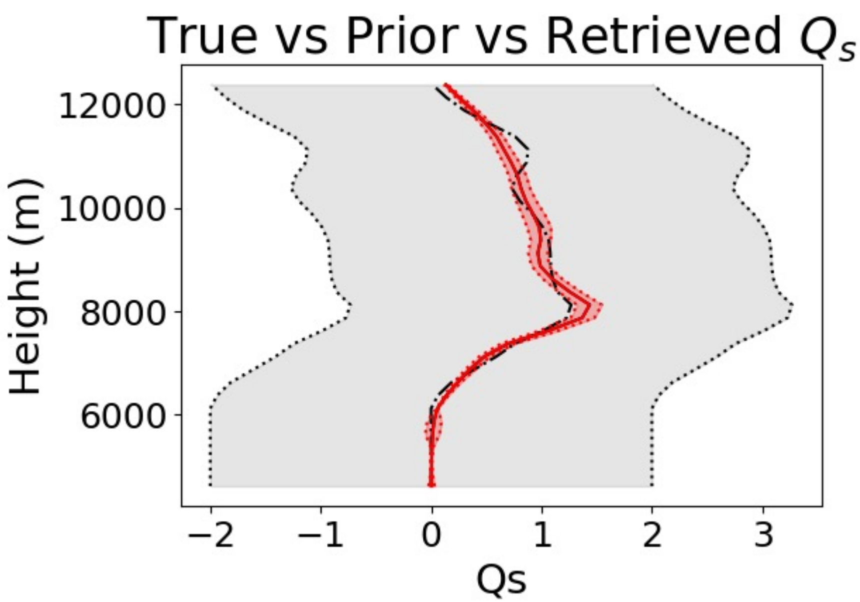
- Next step: apply framework to radar-based retrievals
- Application: evaluate measurement effectiveness for geophysical variables (direct quantification of science traceability)
- Shallow convection rain retrieval
  - Sensitive to radar design parameters (sensitivity, footprint, surface clutter)
  - Important for hydrologic cycle and climate radiation feedbacks
- Quantify retrieval uncertainty using 6000 shallow rain profiles from nature run



Example 3: Snow Retrieval
(ACCP O4)

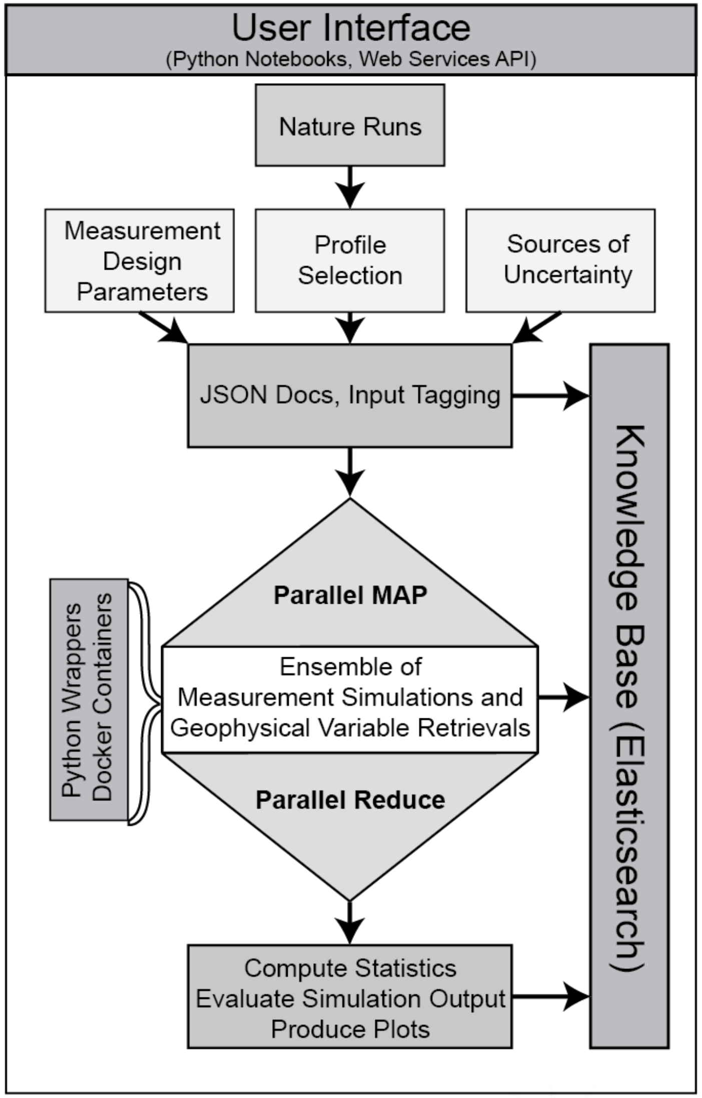
- As with shallow rain retrieval, use Bayesian optimal estimation to quantify uncertainty in snow profile retrievals
- Applications:
  - Multifrequency retrievals from GPM and ACCP
  - Quantification of uncertainty due to ice particle shape and PSD and mis-match among radar footprints
- First test: a perfect retrieval with satellite footprint
  - Known particle shape
  - Known particle size distribution
- Results:
  - Retrieval converges
  - Additional wavelengths provide additional information
- Work in progress:
  - Quantify PSD and shape uncertainty
  - Explore how to combine information from footprints of different sizes

W+Ka+Ku Band



ParOSSE Capability, TRL = 6

- Pluggable nature runs and instrument simulators enable a wide range of trade space studies
- Flexible parallelism enables experiments on diverse architectures and more thorough exploration of uncertainty in measurements and retrievals
- Have implemented various sensitivity analysis techniques
  - Method of Morris, Sobol sensitivity, Monte Carlo, grid search
- Retrievals and DA can utilize several Bayesian methodologies
  - Optimal estimation, MCMC, ensemble Kalman filter, Gamma-Inverse Gamma filter
- Releasing system open source in 2022



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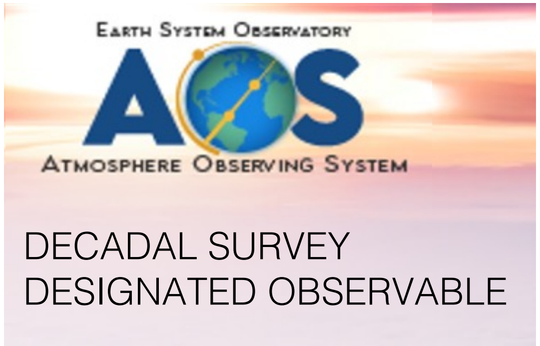
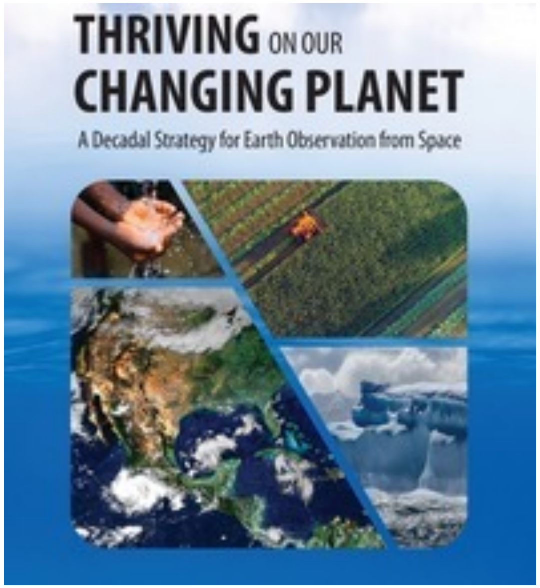
Infusion Case 1: (Actual)
2017 Decadal Survey Atmosphere Observing System

- Currently using the ParOSSE system to quantify uncertainty in radar measurements and retrievals
- Applications to shallow clouds and deep convection
- Informing pre-phase-A activities



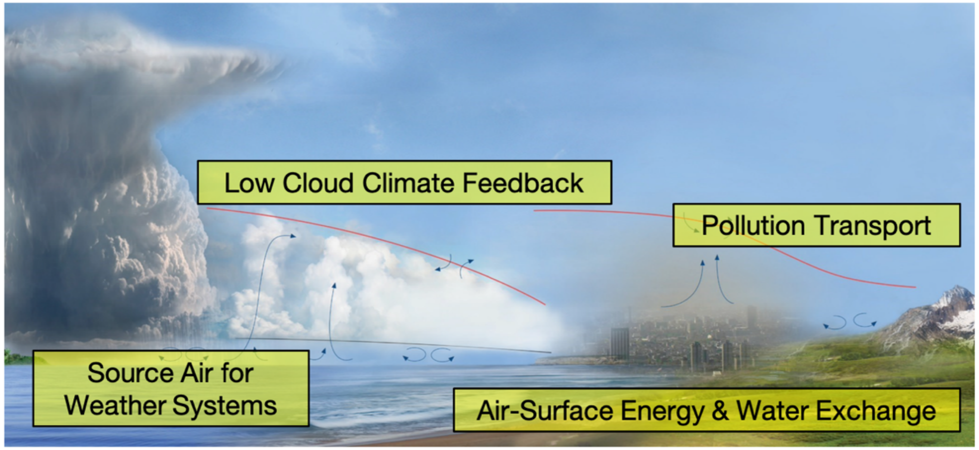


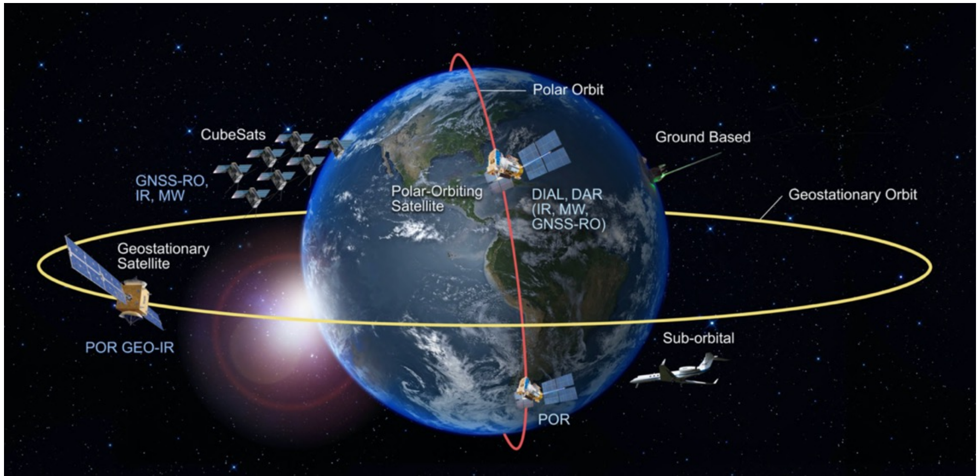
Infusion Case 2: (Planned) NOAA Future Observing System Design

- Planning to use ParOSSE to inform NOAA's next generation mission architecture
- Funded by NOAA/NESDIS/STAR, initiated by Jacqueline LeMoigne
- Joint project with Prof. Paul Grogan (Stevens Institute of Technology) and TAT-C
- Coordination with Sid Boukabara, NOAA-NESDIS-STAR

Infusion Case 3: (Proposed)
NASA Decadal Survey Incubation PBL OSSE

- Proposed to use ParOSSE as a central component of a decadal survey incubation (DSI) planetary boundary layer observing system simulation experiment system
- Uses ParOSSE's modular infrastructure to explore candidate PBL measurements
- Proposal submitted to ROSES '21 DSI A.45

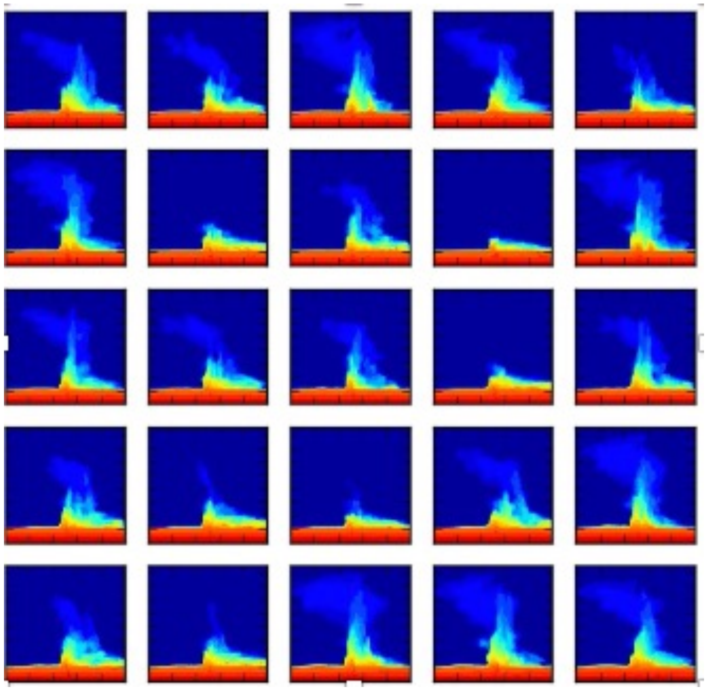




Adapted from the Teixeira et al. (2021) PBL incubation study report, Fig. 8-5.

Infusion Case 4: (Proposed) Digital Twins for Convection-Environment Interaction

- Which observations are necessary to improve state of knowledge of convective storms?
- First: determine which are the most important control variables
- How? Models as a laboratory
- This is a small number of runs of one case, each with a slightly different environment
- Can we scale up to many types of convection in many different environments?
- ParOSSE's flexible configuration makes this straightforward



Cross-section through ensemble of 25 simulations of deep convection, showing transport of pollution from the boundary layer upward into the free troposphere.

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Conference Papers, 2020

Conference Papers:

2020 American Meteorological Society Annual Meeting, Boston, MA

- Posselt, D. J., M. Lebsock, R. L. Storer, M. Minamide, J. Mace, and Z. Xu, *Observing System Simulation Experiments for Convective Clouds*. Talk presented in the 24th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface at the 2020 American Meteorological Society Annual Meeting, Boston, MA, 12-16 January 2020.

- Posselt, D. J., B. D. Wilson, R. L. Storer, E. L. Nelson, N. Niamsuwan, and S. Tanelli, *Observation-Based Cloud and Precipitation Properties from Spaceborne Measurements Using a Parallel Bayesian Retrieval Framework*. Talk presented in the 26th Conference on Probability and Statistics at the 2020 American Meteorological Society Annual Meeting, Boston, MA, 12-16 January 2020.

2020 Fall American Geophysical Union Meeting, Online / Virtual

- Posselt, D. J., B. D. Wilson, R. L. Storer, M. D. Lebsock, G. Duffy, B. Chen, N. Niamsuwan, and S. Tanelli, *Exploring Uncertainty in Bayesian Retrievals of Cloud and Precipitation Properties*, Poster presented at the 2020 Fall American Geophysical Union Meeting, Virtual, 1-17 December 2020.

- Storer, R. L., M. D. Lebsock, and D. J. Posselt, *Quantifying the Effects of Radar Resolution on a Warm Rain Retrieval*, Poster presented at the 2020 Fall American Geophysical Union Meeting, Virtual, 1-17 December 2020.

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Conference Papers, 2021

Conference Papers:

2021 IGARSS

- Posselt, D. J., B. D. Wilson, R. L. Storer, D. Tropf, G. A. Duffy, M. Lebsock, V. Lall, N. Niamsuwan, and S. Tanelli, 2021: *A Science-Focused, Scalable, Flexible Observing System Simulation Experiment (OSSE) Toolkit,* 2021 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)

2021 Fall American Geophysical Union Meeting, New Orleans, LA / Virtual

- Posselt, D. J., B. D. Wilson, R. L. Storer, D. Tropf, G. Duffy, M. D. Lebsock, V. Lall, and S. Tanelli, *ParOSSE: A Flexible Parallel Bayesian Framework for Quantifying Uncertainty in Measurements and Retrievals of Clouds and Precipitation*, Poster presented at the 2021 Fall American Geophysical Union Meeting, New Orleans, LA, 13-17 December 2021.

- Wilson, B. D., V. Lall, D. Tropf, D. J. Posselt, and R. L. Storer, *The PARMAP Python Library: Fast, Scalable, Cheap and Easy Serverless Computing for Every Scientist*, Poster presented at the 2021 Fall American Geophysical Union Meeting, New Orleans, LA, 13-17 December 2021.

- Storer, R. L., M. D. Lebsock, and D. J. Posselt, *Quantifying the Effects of Radar Resolution on a Warm Rain Retrieval*, Poster presented at the 2021 Fall American Geophysical Union Meeting, New Orleans, LA, 13-17 December 2021.

Peer Reviewed Publications

- Posselt, D. J., B. D. Wilson, R. L. Storer, D. Tropf, G. A. Duffy, M. Lebsock, V. Lall, N. Niamsuwan, and S. Tanelli, 2021: A Science-Focused, Scalable, Flexible Observing System Simulation Experiment (OSSE) Toolkit, 2021 IEEE International Geoscience and Remote Sensing Symposium (IGARSS).

- Duffy, G. A., and D. J. Posselt, 2021: A particle size distribution model for falling snow aggregates. J. Appl. Meteor. Clim., Accepted.

- Vukicevic, T., D. J. Posselt, and A. Stankovich, 2021: Sensitivity of modeled microphysics to stochastically perturbed parameters. Submitted.

- Posselt, D. J., B. D. Wilson, R. L. Storer, D. Tropf, V. Lall, G. A. Duffy, and M. Lebsock, 2022: Large-Scale Cloud and Precipitation Retrieval Uncertainty Quantification. In Preparation.

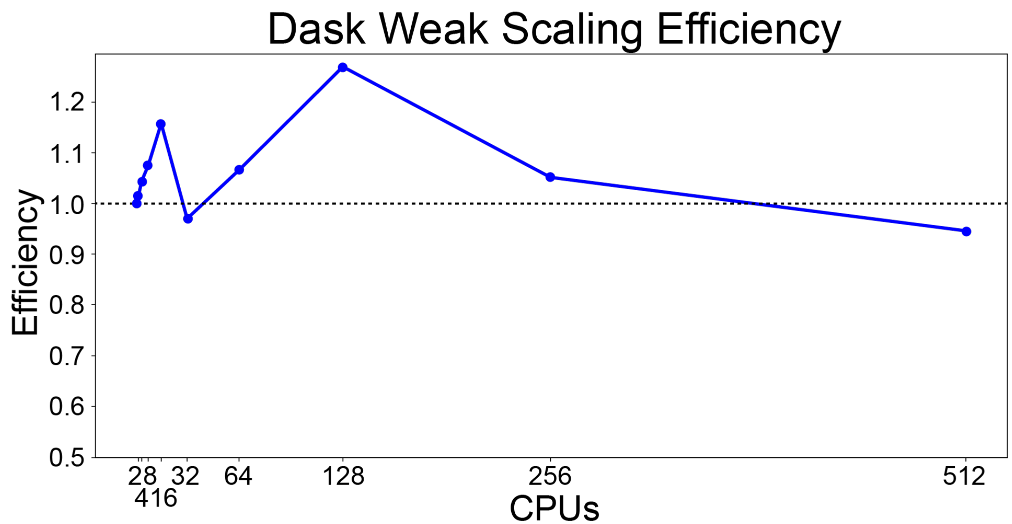
List of Acronyms

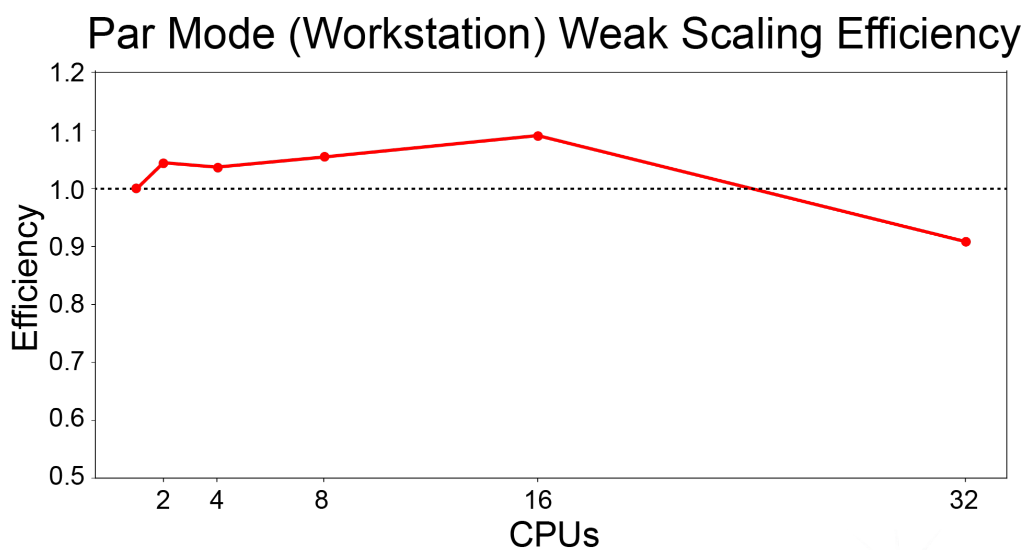
ACCP	Aerosols and Clouds, Convection, and Precipitation
AOS	Atmposphere Observing System
DO	Designated Observable
DS	Decadal Survey
DSI	Decadal Survey Incubation
G5NR	GEOS-5 Nature Run
GEOS	Global Earth Observing System
GPM	Global Precipitation Mission
NEOS3	NASA Earth Observing System Simulator Suite
NESDIS	National Environmental Satellite Data and Information Service
NR	Nature Run
OSSE	Observing System Simulation Experiment
ParOSSE	Parallel OSSE
PBL	Planetary Boundary Layer
RAMS	Regional Atmospheric Modeling System
TAT-C	Tradespace Analysis Toolkit for Constellations
TBC	To Be Completed
UQ	Uncertainty Quantification
WRF	Weather Research and Forecasting model

Parallel OSSE System (ParOSSE) Performance

- Sensitivity and retrieval experiments are embarrasingly parallel (can be done nearly independently)
- ParMAP library makes ParOSSE deployable on a single machine (Par), cluster (Dask), and the cloud (AWS Lambda Functions)
- Our initial tests have indicated excellent scaling efficiency*

*Efficiency > 1 is due to I/O limitations with a single CPU





Background / Objectives / Tech Advance

Project Summary: Objectives, Technology, and Science Goals

- **Objective**: Construct a software architecture capable of rapidly and thoroughly evaluating mission science objectives / architecture components (OSSE)
- **Technology**: Pluggable instrument simulators connected to Spark MAP-REDUCE analytics, Jupyter notebook workflows, and ElasticSearch database
- **Science Goals**: Evaluate spaceborne radar/radiometer measurements of hydrometeors and dynamics in shallow and deep convection

R&A and Applications Science Goals for *Weather* and *Water & Energy*

- Advances in understanding the dynamics of weather systems, and their transport of water and energy will require new observing systems and new measurement techniques
- The parallel OSSE toolkit provides a quantitative means for evaluation of new measurement techniques and observing systems, in the context of a SATM

2017 Decadal Survey Aerosols and Clouds, Convection and Precipitation

- Radar/radiometer retrievals and uncertainty quantification directly relevant to all four cloud-related science objectives

ParOSSE Technical Advances

- **Build a flexible system that is applicable to a broad variety of mission concepts**
- Combine measurement simulators and Bayesian retrieval with a Parallel Map-Reduce framework
  ➔ Pervasive parallel computing
- Containers for Pluggable measurement simulators
  - "app store" of pluggable algorithms
- Flexible Knowledge Database
  - Search for & group experiment outputs by tags & run metadata
  - Fast ensemble statistics, comparisons, drill-down
- Map-Reduce framework & cluster/GPU computing to:
  - Generate large database of simulations – geophysical variable (retrieval) pairs
  - Compute analytics to determine whether measurements satisfy mission requirements

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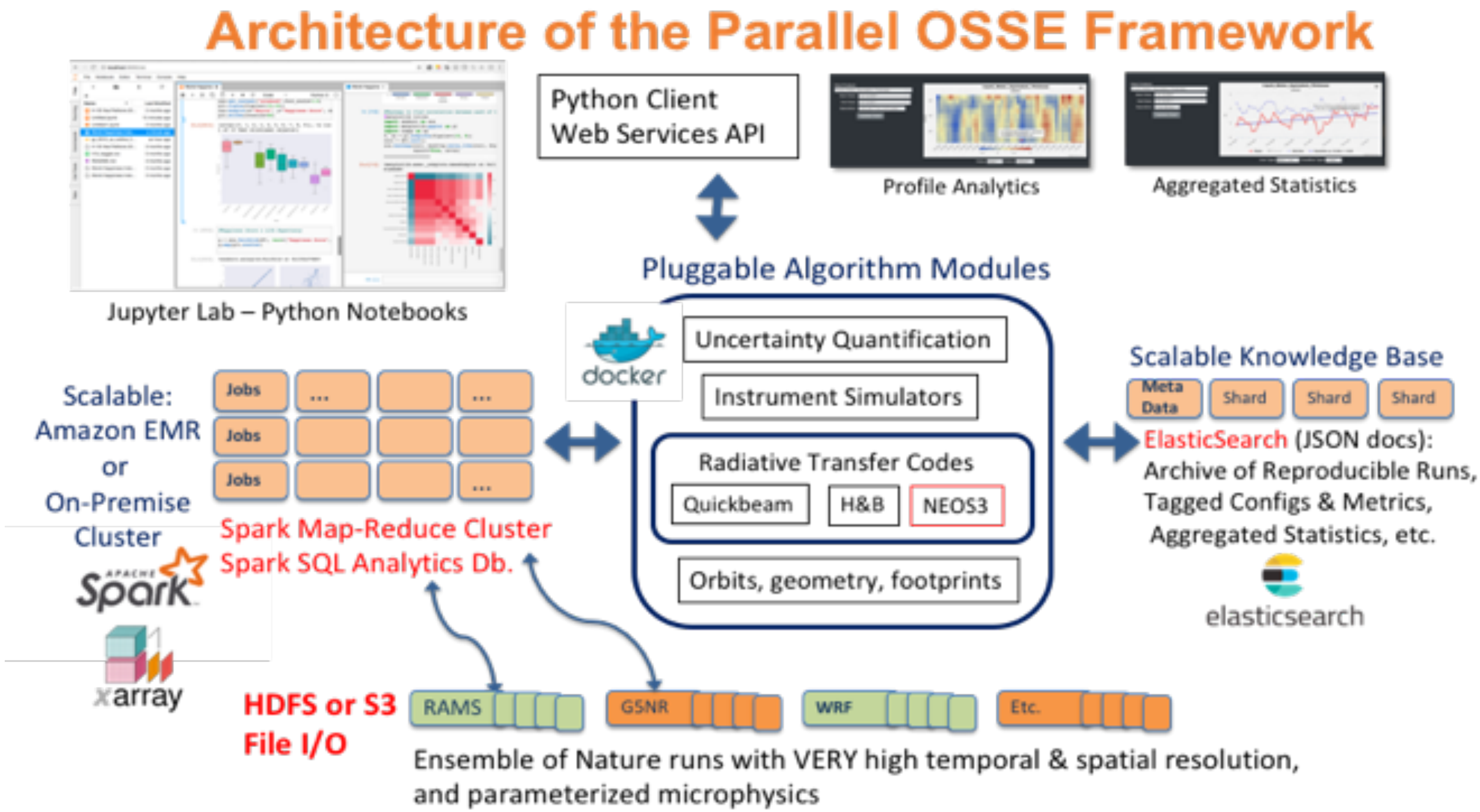
Technology Directions

- Parallel / GPU Computing is mandatory
  - Clock speeds flat since 2005
  - Moore's law → many-core, GPU as supercomputer
  - Apple M1 SoC: CPU, GPU, Neural Engine accessing same shared memory (unified memory architecture)
- VM's → Containers → Serverless
  - Functions as a Service
  - Python + Fortran executables run in Container
  - 6.4 Million radar simulator runs using AWS Lambdas: <50 minutes for ~$150 (compute is cheap)
- All software will soon contain trained Machine Learning models

ParOSSE Architecture



The basic architecture of the OSSE system, including the Map-Reduce compute cluster (Apache Spark, Xarray/dask cluster, or scalable Lambda functions), the scalable Knowledge Base (ElasticSearch), a set of "pluggable" code modules, and Python Live Notebooks or web services as front-ends.

Future of Parallel OSSE Toolkit: Digital Twins and Model Uncertainty

Model Components

Sources of Variability

Initial Conditions
Model Parameterizations

Pluggable Models

Cloud Resolving Models
Simple Process Models

Ensembles and DA

Grid Search
Monte Carlo
Latin Hypercube
Ensemble Kalman Filter

ParMAP: Flexible Parallelism

Standalone Workstation

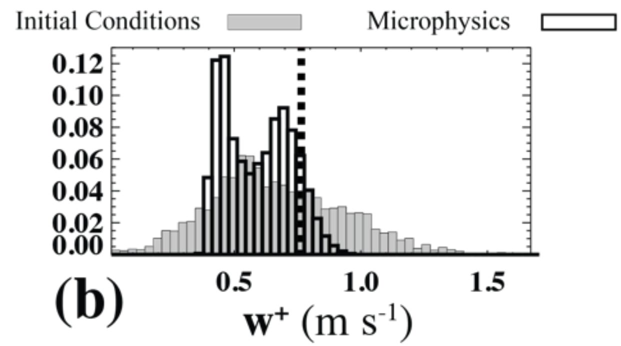
Clusters and HPC

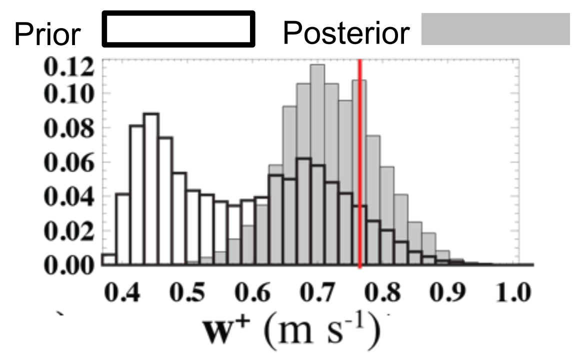
Cloud Computing

aws

Uncertainty Analysis and Data Assimilation

Model Sensitivity





Data Assimilation

Digital Twin Ensembles, Guidance for Model Improvement, and Data Assimilation

Digital Twins: Convection-Environment Interaction

- Which observations are necessary to improve state of knowledge of convective storms?
- First: determine which are the most important control variables
- How? Models as a laboratory
- This is a small number of runs of one case, each with a slightly different environment
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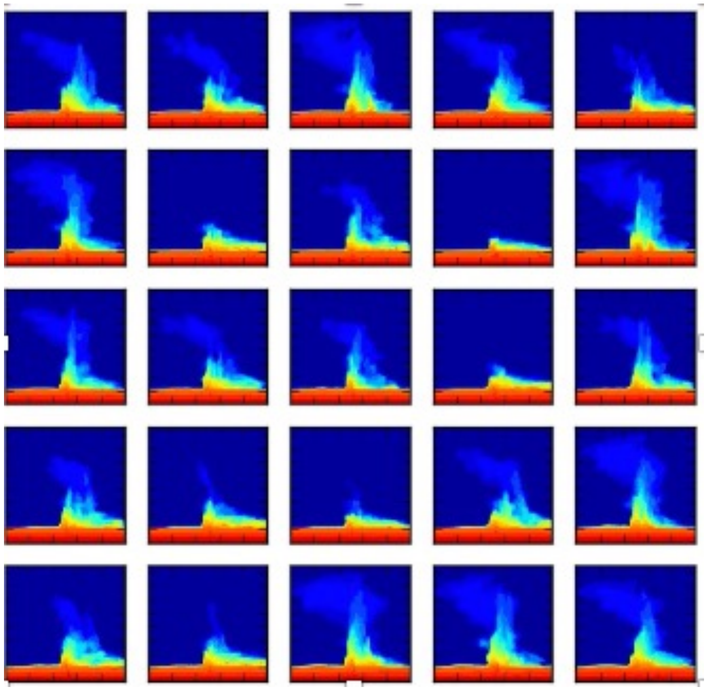
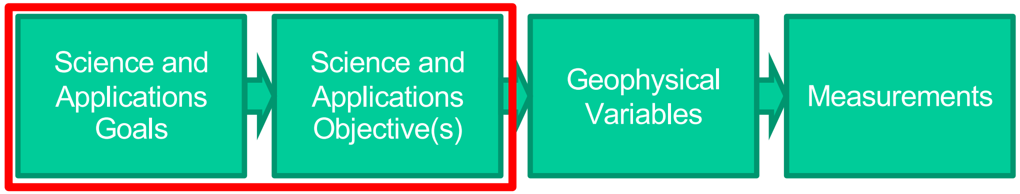
- ParOSSE’s flexible configuration makes this straightforward



Cross-section through ensemble of 25 simulations of deep convection, showing transport of pollution from the boundary layer upward into the free troposphere.

Future of Parallel OSSE Toolkit: Left Hand Side of SATM



Can we quantify ability to meet science and applications goals and objectives?

Can we create ensembles of digital twin simulations?

Science:

- Quantify state of knowledge: span range of weather and climate outcomes
- Models as a laboratory, and ensembles as the tool.
- ParOSSE is flexible - spawn ensembles of *process simulations* and assess outcomes and potential for reduction in uncertainty (metrics from information theory, ensemble forecasting, etc)

Applications:

- Assess data sufficiency for mission design, spanning a large design trade space
- Map from GV uncertainty to uncertainty in stakeholder quantities of interest (e.g., rainfall duration and intensity vs. needs of reservoir managers)

Integrating TAT-C, STARS, and VCE for New Observing Strategy Mission Design

Paul T. Grogan (PI, Stevens Institute of Technology)

QRS-20-0001 Group Technical Review
Grant No. 80NSSC20K1118
January 7, 2022

Joel Johnson, Christopher Ball, Andrew O'Brien (Ohio State University)
Matt French, Marco Paolieri (University of Southern California)
Josue Tapia-Tamayo, Isaac Feldman (Stevens Institute of Technology)

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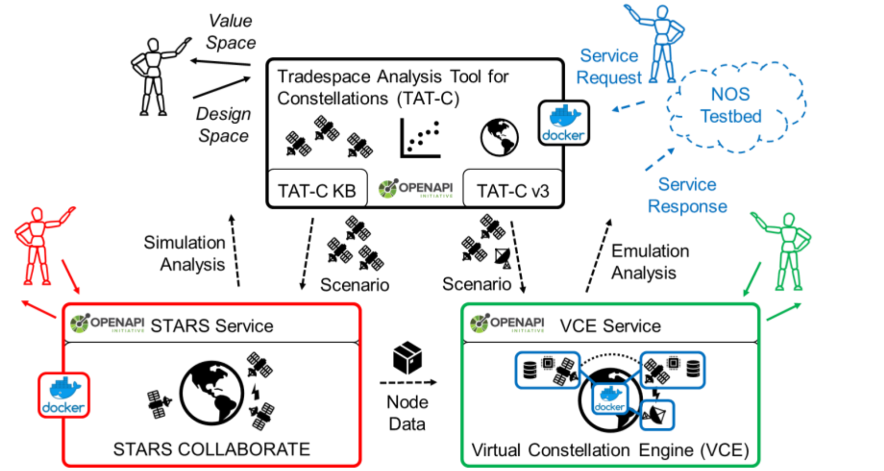
Integrating TAT-C, STARS, and VCE for New Observing Strategy Mission Design

PI: Paul Grogan, Stevens Institute of Technology

Objective

- Inform selection and maturation of Pre-Phase A distributed space mission concepts
  - TAT-C: architecture enumeration and high-level evaluation (cost, coverage, quality)
  - STARS: autonomous/adaptive sensor interaction (COLLABORATE)
  - VCE: onboard computing and networking
- Expose tools as services to NOS Testbed efforts
  - Tools accessed individually or in concert to support concept development
  - Loosely-coupled service-oriented API



STARS and VCE support TAT-C and all interface with NOS-T

Approach

- Identify initial set of services to expose
- Define and align interface vocabulary
- Refactor tool interfaces: sequential operation
  - Use TAT-C output as STARS/VCE input
  - Broad set of loosely-coupled services
- Refactor tool interfaces: integrated operation
  - Call STARS/VCE in TAT-C workflow
  - Selective set of tightly-coupled services
- Documentation and deployment/release

Co-Is: C. Ball, A. O'Brien, J. Johnson / OSU, M. Paolieri and M. French / USC ISI

Key Milestones

- Develop service API vocabulary (v1): Sep '20
  - Adopted OpenAPI (REST/HTTP)
  - JSON Object Schema
- Demonstrate sequential operation: Dec '20
  - Development servers operational
  - Virtualization containers (Docker)
- Demonstrate integrated operation : May '21
- Release updated software tools: Aug '21
- Application to model NOAA systems Mar '22

Entry TRL: 3, Current TRL: 5

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Background

Tradespace Analysis Tool for Constellations (TAT-C)

Enumerate and evaluate combinatorial design spaces for distributed space missions

- Order-of-magnitude cost
- Coverage statistics

Simulation Toolset for Adaptive Remote Sensing (STARS)

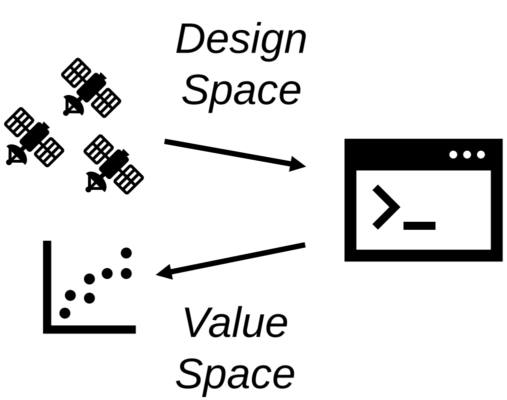
Simulate autonomous and collaborative satellite networks

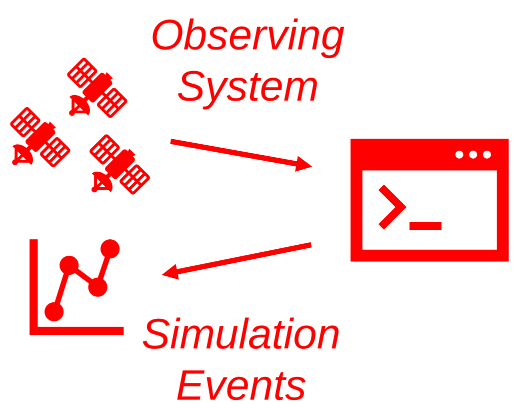
Observing system simulation experiments (OSSEs) to evaluate scientific return

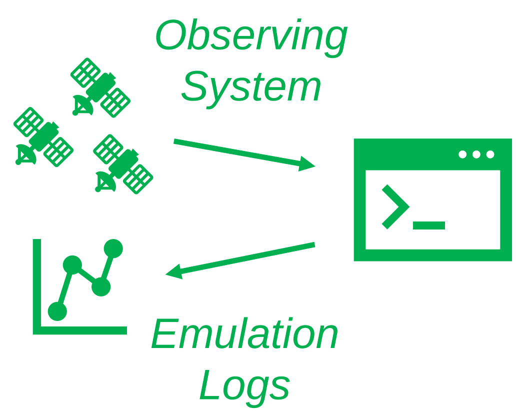
Virtual Constellation Engine (VCE)

Emulate distributed, multi-satellite operations

Emulate network and instrument operation and monitor resource consumption

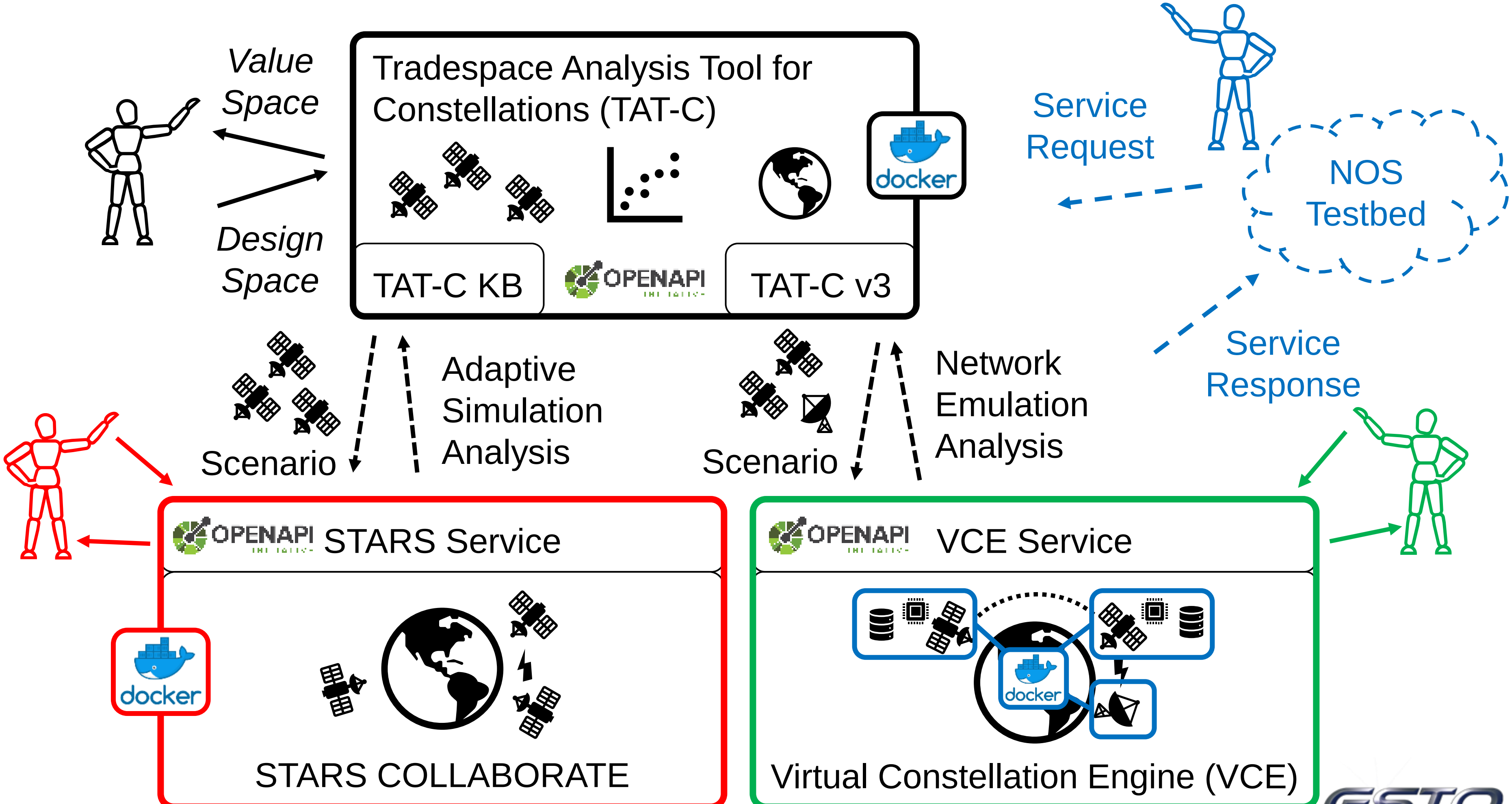






Project Objectives

Integrate TAT-C, STARS, and VCE analysis capabilities to evaluate and mature mission concepts for New Observing Strategies (NOS).



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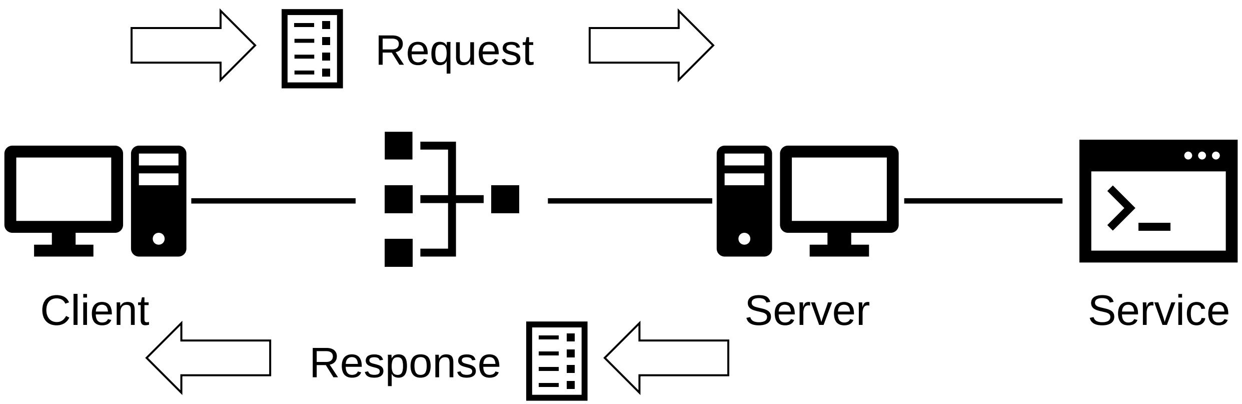
OpenAPI Standard

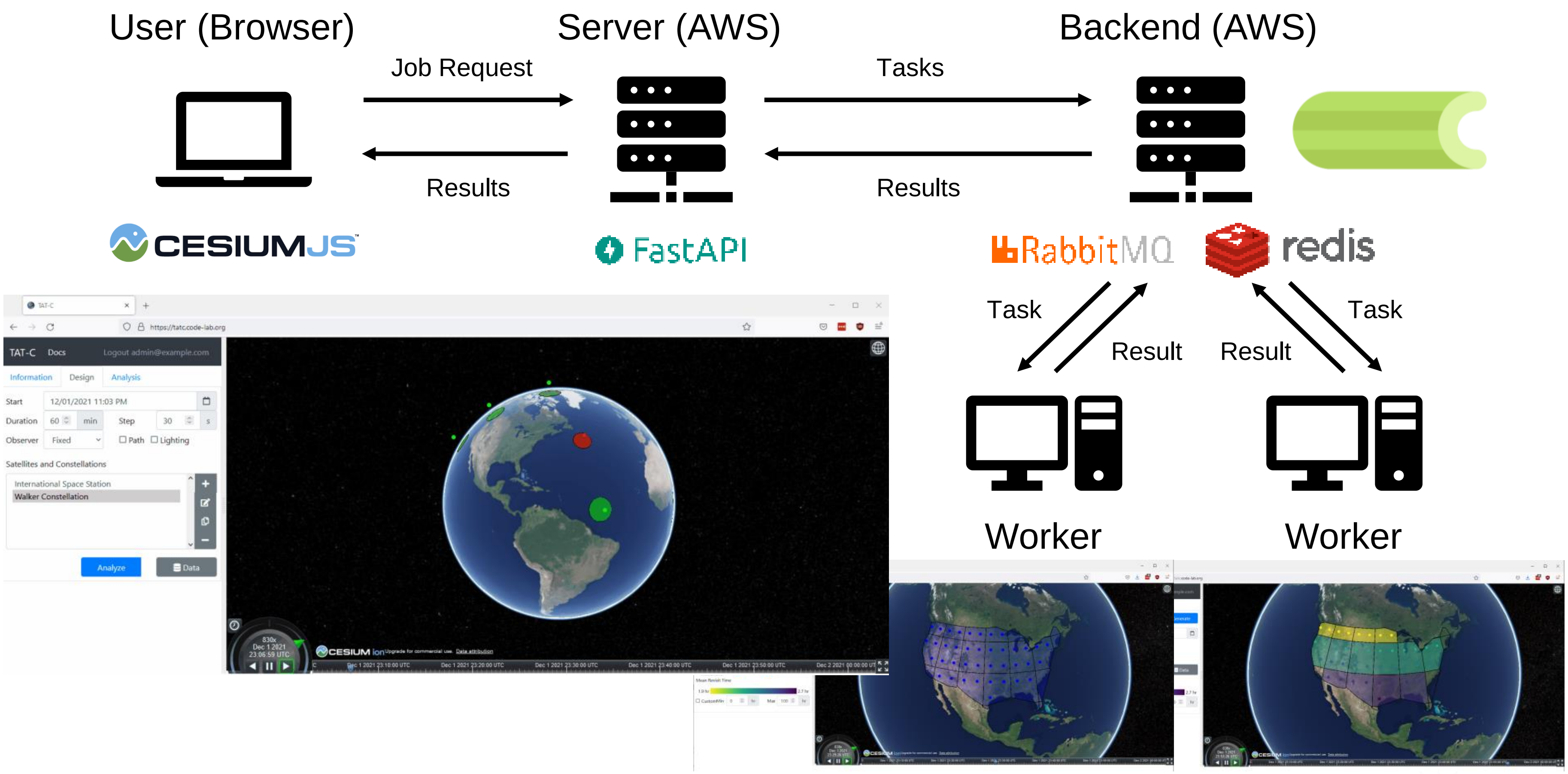
- Common adoption of OpenAPI (previously Swagger) standard describes tool interfaces as HTTP requests
  - Documented in JSON or YAML format
  - Can be auto-generated from Python (Pydantic/FastAPI)



- Document *paths* as HTTP service endpoints
- Document *schemas* as request/response objects
- No software installation/configuration for clients

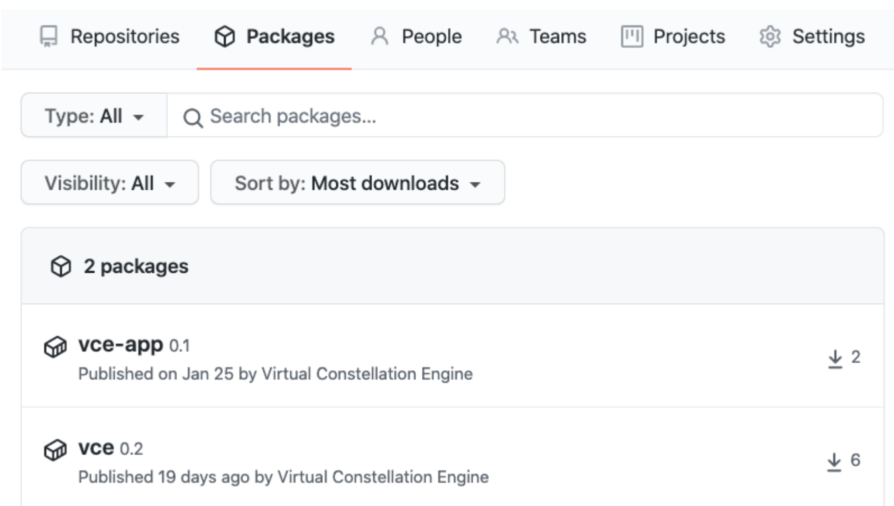
TAT-C Service Overview

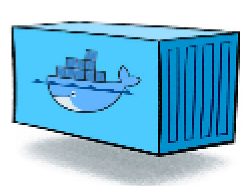
- TAT-C development server software architecture
  - Student-led projects for verification and validation testing

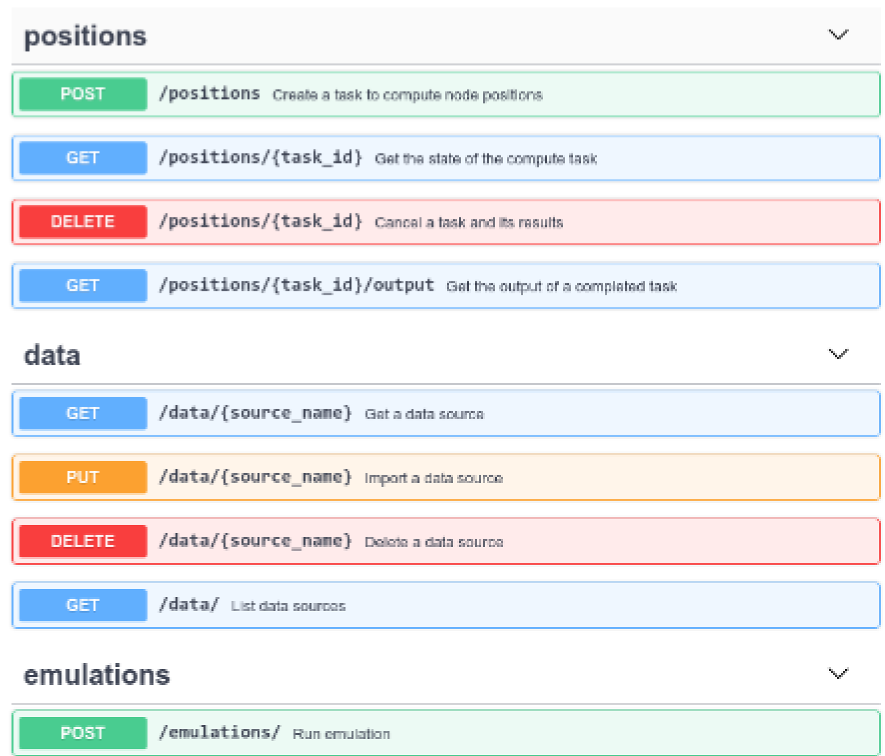


VCE Service Overview

- VCE framework packaged as a Docker container using the GitHub Container Registry
- All VCE functions accessible through a REST API



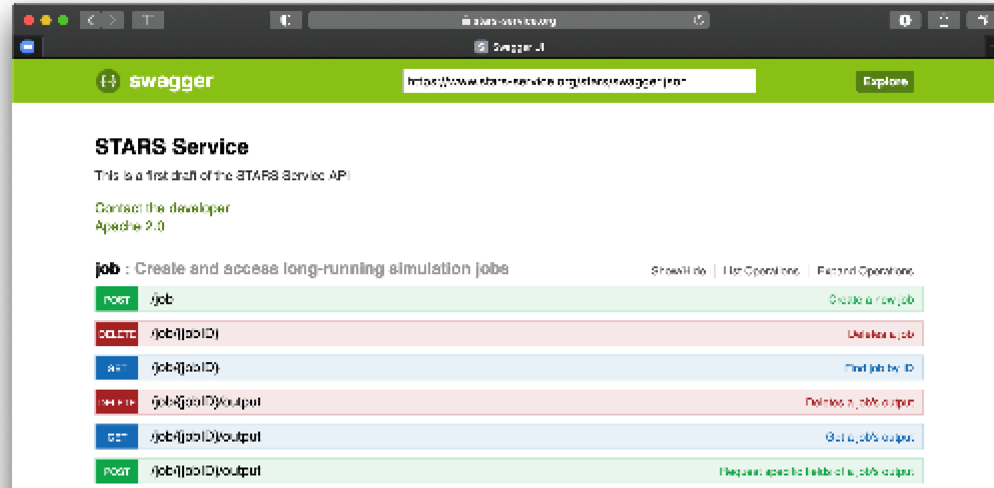




STARS Service Overview

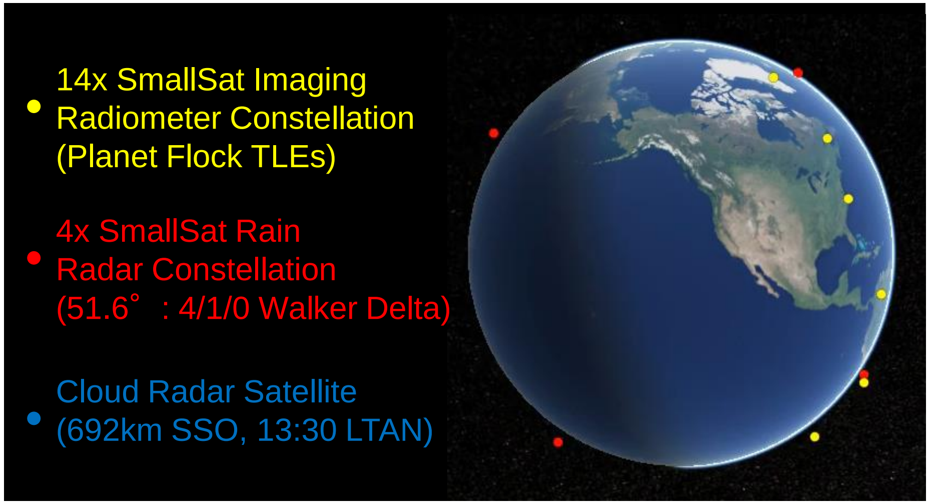
Created a new interface to the STARS simulation tools that allow it to be invoked as a service (by a user or by TAT-C).

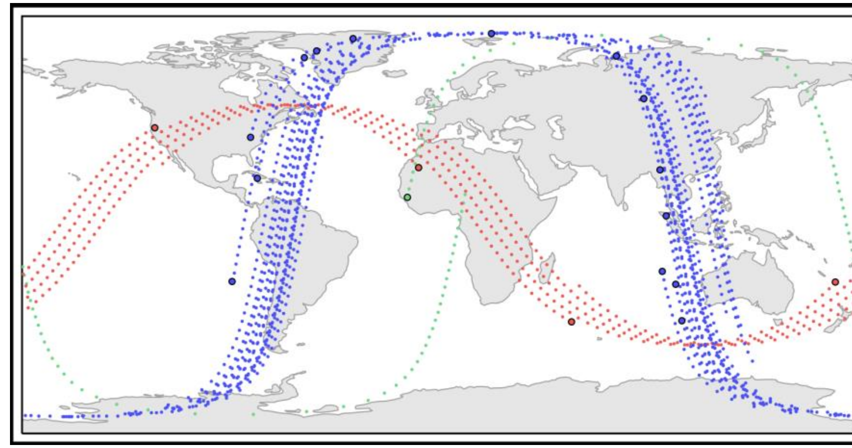
- **Packaging STARS into a Container** –STARS C++ library packaged into a portable Docker container for easy distribution
- **Developing the STARS Service API** – STARS Service API (i.e., a REST API accessed using HTTP) was written and implemented to simplify user access
- **Deploying STARS Service:** STARS Service deployed on Amazon Web Services (AWS) for joint use by TAT-C/STARS/VCE team and future implementation on NASA cloud platforms

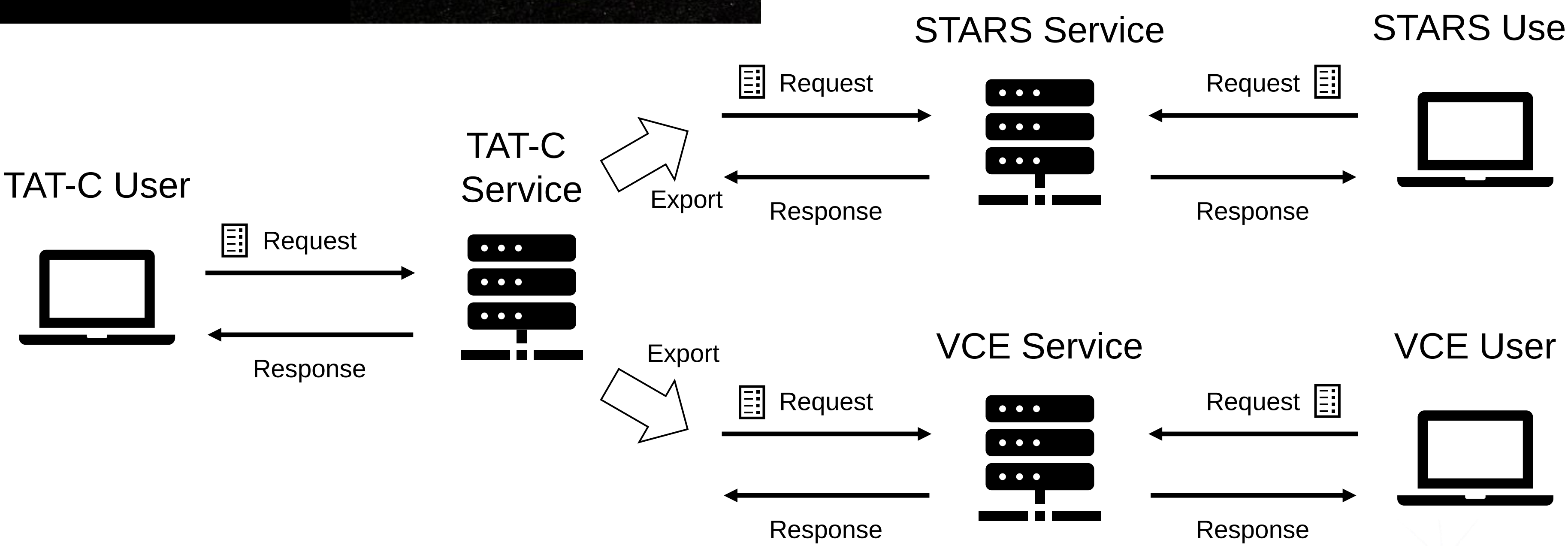


- **Integrating GEOS 5:** STARS Service accepts GEOS 5 Nature Run data for Earth science simulations

Integrated Analysis Environment







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Summary of Accomplishments

- Adopted common web-based interface standard:
  - OpenAPI (formerly Swagger): standard, language-agnostic software interface to RESTful APIs
  - Human- and machine-readable format
  - Supported by FastAPI Python library for easy development
- Incrementally developed object schemas (JSON Schema)
- Incrementally developed API services (OpenAPI):
  - STARS service wrapper to build and execute simulations
  - VCE service to propagate orbits and configure emulations
  - TAT-C KB and analysis (coverage and revisit) endpoints
- TAT-C development and testing server operational: tatc.code-lab.org

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Actual or Potential Infusions and Collaborations

- Infusion:
  - TAT-C technology used in several AIST-21 proposals and NIP project: Co-simulation for Partnerships to Observe Convective Storm Systems (80NSSC21K1515; PI: Grogan)
- Transition:
  - TAT-C interest expressed by GSFC IDC and NOAA/NESDIS
- Technology transfer:
  - TAT-C v.3 open-source release (BSD license) in Jan 2022
  - STARS COLLABORATE and STARS Service available on GitHub: https://github.com/aobrien/stars-service
- Collaborators/Contacts:
  - Sid Boukabara (NOAA/NESDIS), Jennifer Bracken (GSFC IDC), Koki Ho (Georgia Tech), Derek Posselt (JPL), Carrie Vuyovich (GSFC), Danielle Wood (MIT)

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Publications

- Ball, Grogan, Tapia-Tamayo, O'Brien, Johnson, French, and Paolieri**, "Integrated constellation analysis tools to support New Observing Strategy mission design"** *SPIE Optical Engineering + Applications: CubeSats and SmallSats for Remote Sensing V,* August 2021*.*
- Grogan and Tapia-Tamayo "**Using JSON Schema to Model Satellite Systems in the Tradespace Analysis Tool for Constellations**" submitted to *IEEE Systems Conference*, April 25-28, 2022.
- Tapia-Tamayo and Grogan, "**Tradespace Analysis of Cross-Calibration in Missions Observing Ocean Color**" submitted to *IEEE Systems Conference*, April 25-28, 2022.
- Tapia-Tamayo, Feldman, and Grogan, "**Towards Scalable and Interoperable Model-centric Engineering Artifacts using RESTful APIs and Distributed Task Queues**" in preparation for *Systems Engineering* journal.

List of Acronyms

API	Application Programming Interface
BSD	Berkeley Source Distribution
HTTP	Hypertext Transfer Protocol
KB	Knowledge Base
NOS	New Observing Strategies
OSSE	Observing System Simulation Experiment
REST	Representational State Transfer
STARS	Simulation Toolset for Adaptive Remote Sensing
TAT-C	Tradespace Analysis Tool for Constellations
VCE	Virtual Constellation Engine

New Observing Strategies Testbed (NOS-T) Design and Development

Paul T. Grogan (PI, Systems Engineering Research Center)

ART-015 Group Technical Review
Contract No. W15QKN-18-D-0040, Task Order W15QKN20F0551
January 7, 2022

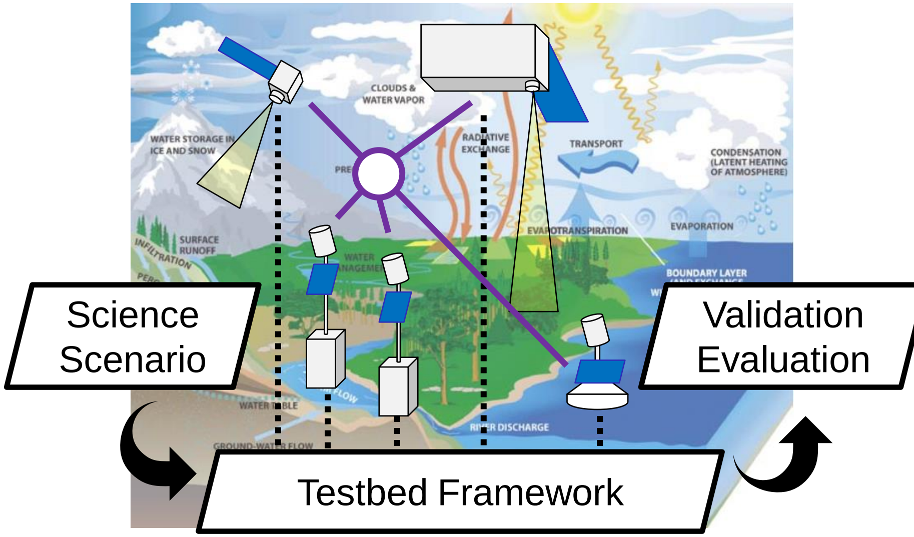
Jerry Sellers, Matthew LeVine, Brian Chell, Leigha Capra
(Systems Engineering Research Center)

New Observing Strategies Testbed (NOS-T) Design and Development

PI: Paul Grogan, Systems Engineering Research Center

Objective

- Design and develop the NOS-T framework for disparate organizations to propose and participate in developing NOS software and information systems technology capabilities and services
    - Individually validate new NOS technologies
    - Debug and demonstrate novel NOS concepts
    - Compare competing technologies
    - Socialize NOS technologies and concepts
- Identify appropriate NOS-T governance model
- Identify appropriate NOS-T concept of operations



Approach

- Enterprise system architecting processes
    - Identify and trace value streams for program objectives
    - Model-based systems engineering methods for traceability
- Loosely-coupled information system architecture
    - Achieve nonfunctional requirements such as modularity, extensibility, security, and scalability
    - Provide technical functions such as data distribution, time synchronization, and interoperability
- Engage with Earth Science community to support emerging NOS technologies and scenarios of interest
    - Adopt representative Earth Science use case
    - Demonstrate proposed NOS-T technology for community

Key Milestones

- Framework Design v1.0: Nov. 8, 2020
    - Initial architecture/governance/operations
    - Development plan
- Framework Architecture v1.0: May 5, 2021
    - Refine requirements
    - Propose architecture
- Framework Development v1.0: Feb. 1, 2022
    - Define representative use case
    - Perform framework demonstration
    - Develop Interface Control Document
- Framework Design v2.0: Nov. 7, 2022
- Framework Development v2.0: Aug. 4, 2023

Entry TRL: 2 Current TRL: 4

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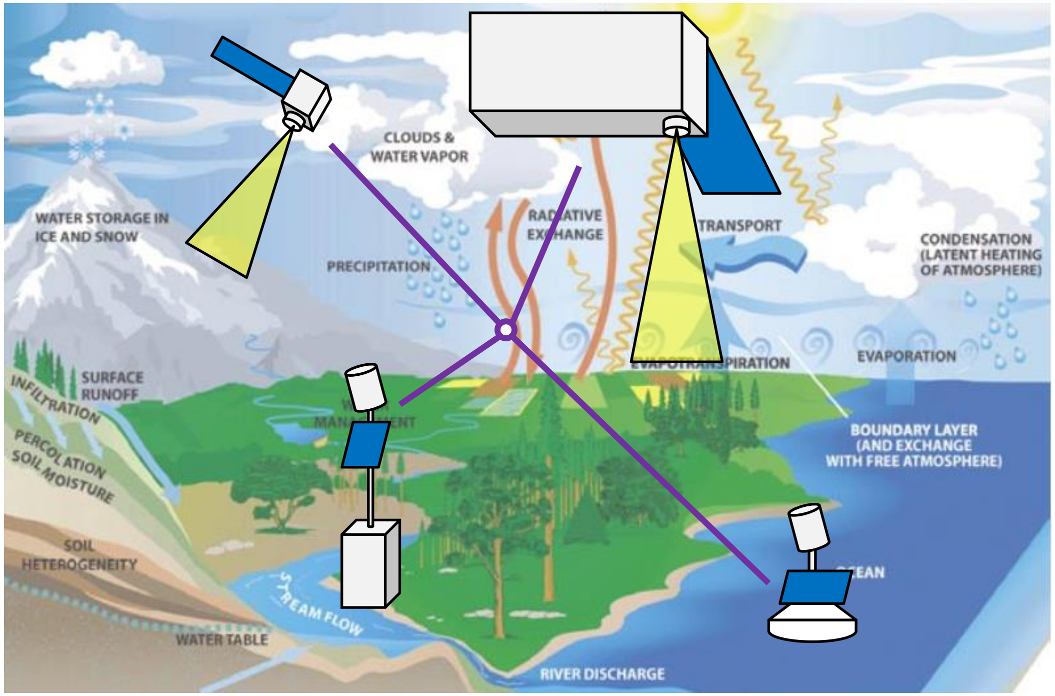
Background: New Observing Strategies Testbed (NOS-T)



- Validate NOS technologies, independently and as a system
- Demonstrate novel distributed operational concepts
- Enable meaningful comparisons of competing technologies
- Socialize new technologies and concepts with the science community by significantly retiring the risk of integration

NOS-T Framework Objectives

- **Enable disparate organizations to propose and participate in developing NOS software and information technology using the Testbed**

Geographic distribution: interconnect using standard network interfaces

Modularity: add/update components without modifying the testbed

Multi-party participation: exchange information via standard network protocols

Extensibility: vary size or capabilities to explore a wide range of test cases

Security: encrypt transport, enforce access control, monitoring on authorized information systems

Usability: Earth science community members can develop test cases without a substantial learning curve

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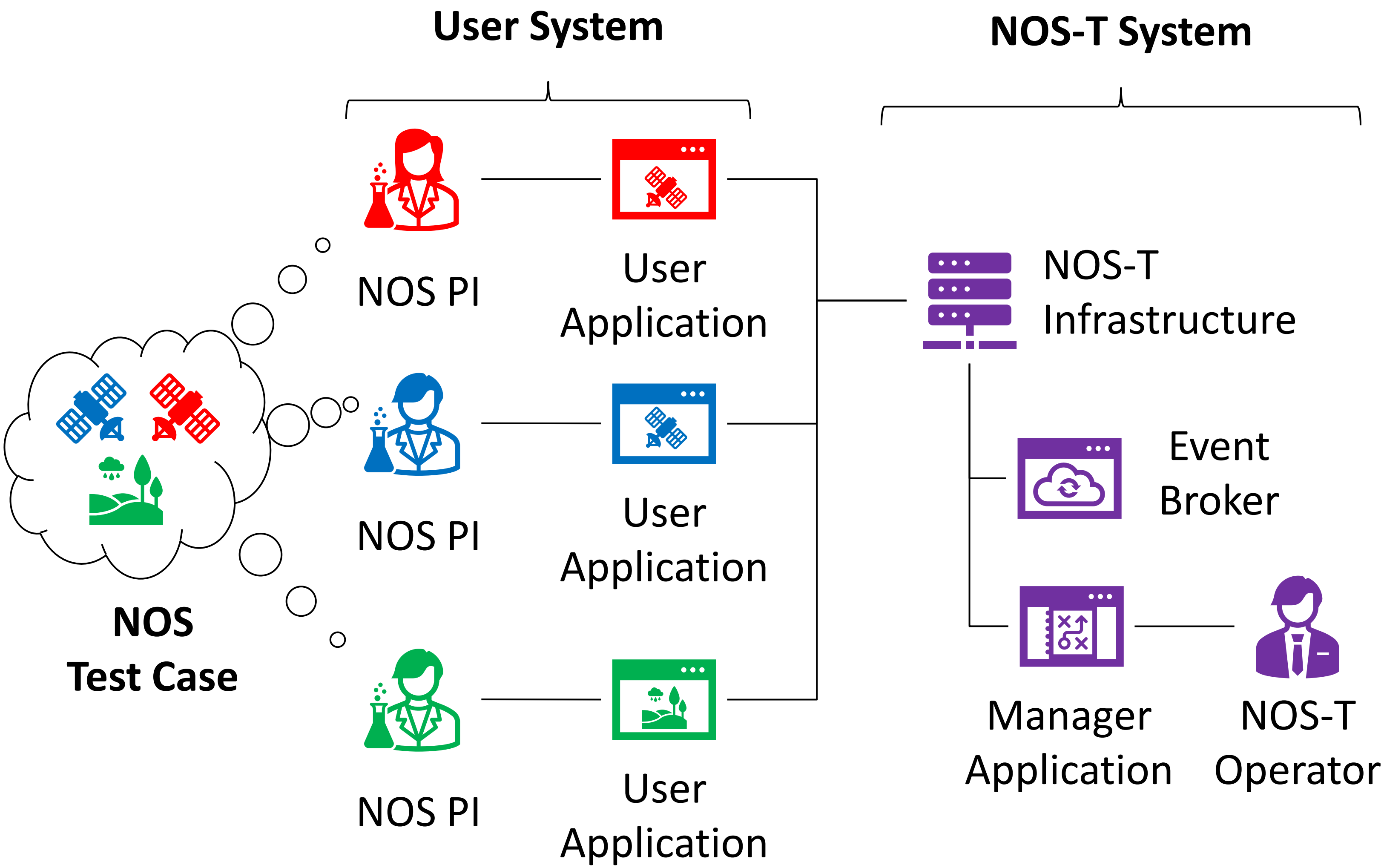
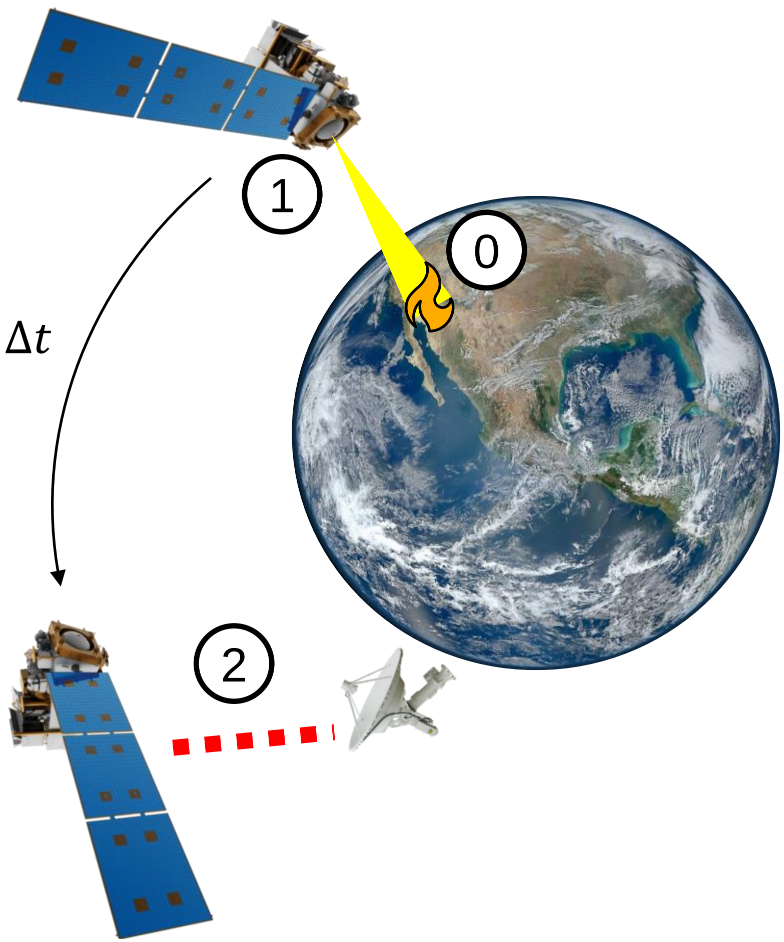
NOS-T System Architecture



Application Case: FireSat+



- Fire hazard detection in continental U.S.
  - Initiate fires using 2020 VIIRS data
  - Remote observation by three-satellite constellation
  - Data downlink to ground station
  - Evaluate key performance measures (observation latency)
- Extensible to design-of-experiment studies to assess observation system variables

5-day (at 60x scale) Scenario; ~90x playback

= Ground Station

= Fire Started

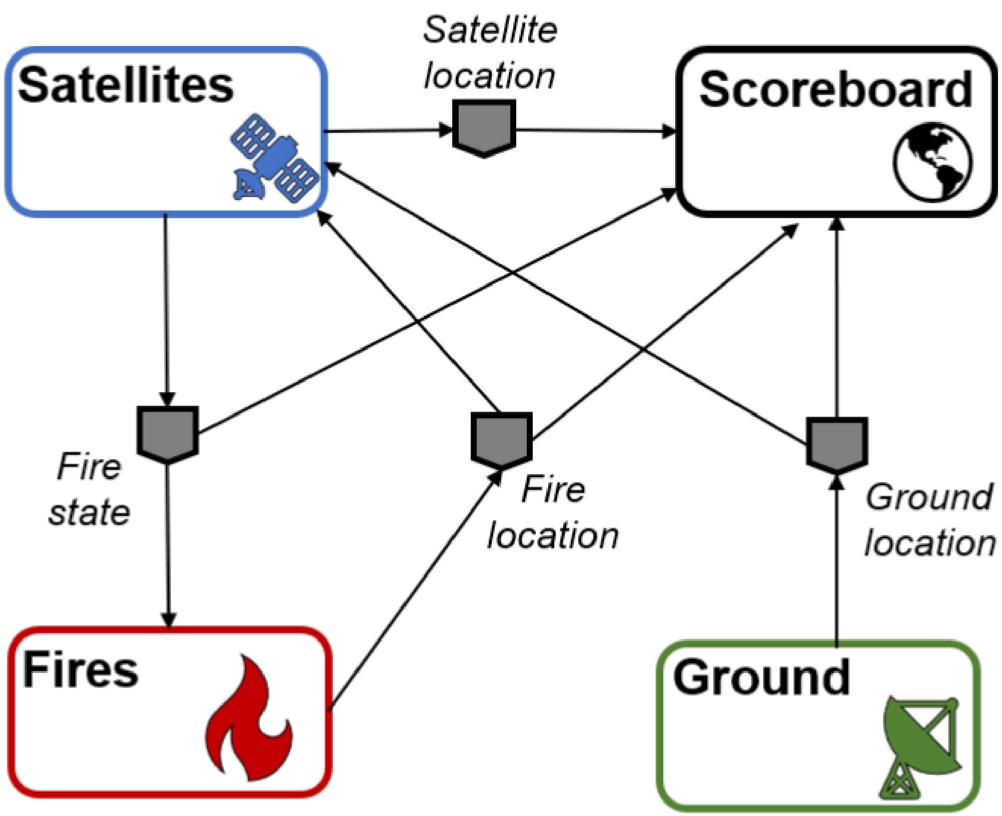
= Fire Reported

= Satellites

= Fire Detected

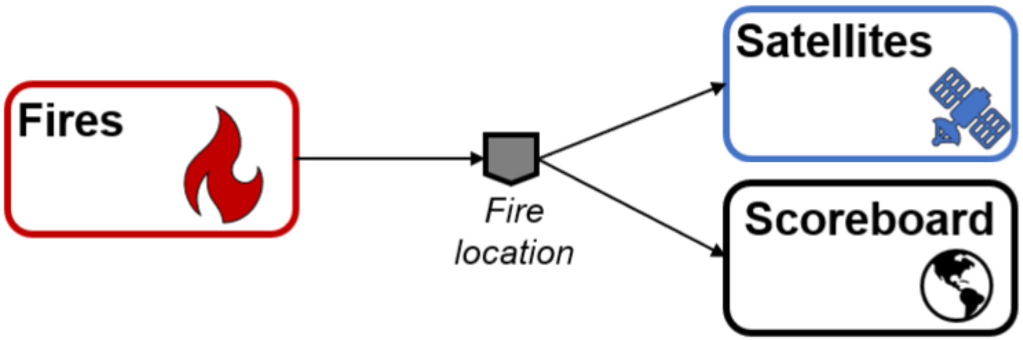
Earth Science Technology Office

FireSat+ Test Case Architecture



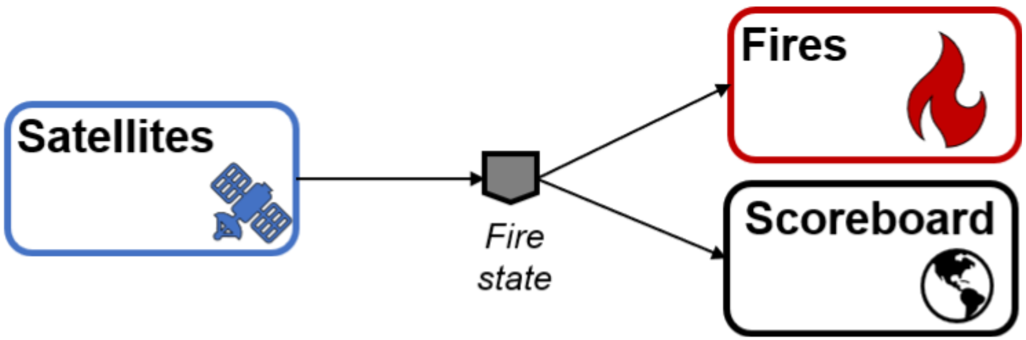
- **Fires:** publishes fire location, records times started/detected/reported
- **Ground:** publishes ground station location
- **Satellites:** models orbit propagation, detects fires, reports fires when link to Ground is possible
- **Scoreboard:** displays graphical representation of mission

FireSat+ Interface Sample



`$PREFIX/fires/location`

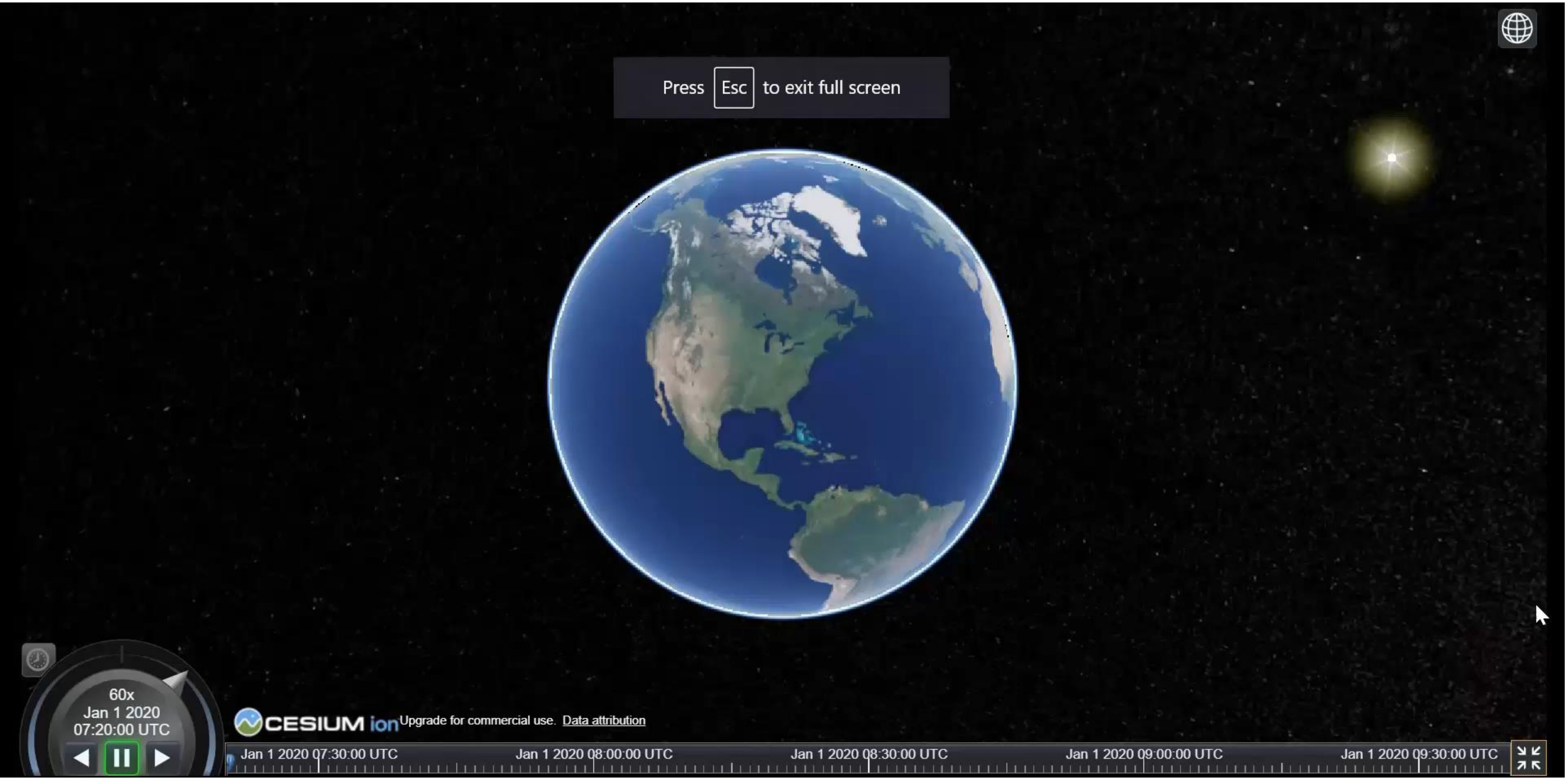
Payload: fire ID, fire latitude, longitude, start time



`$PREFIX/satellite/detected`
`$PREFIX/satellite/reported`

Payload: fire ID, satellite ID, state change time, fire state

Extended (Global) Scenario



= Ground Station = Fire Started = Fire Reported

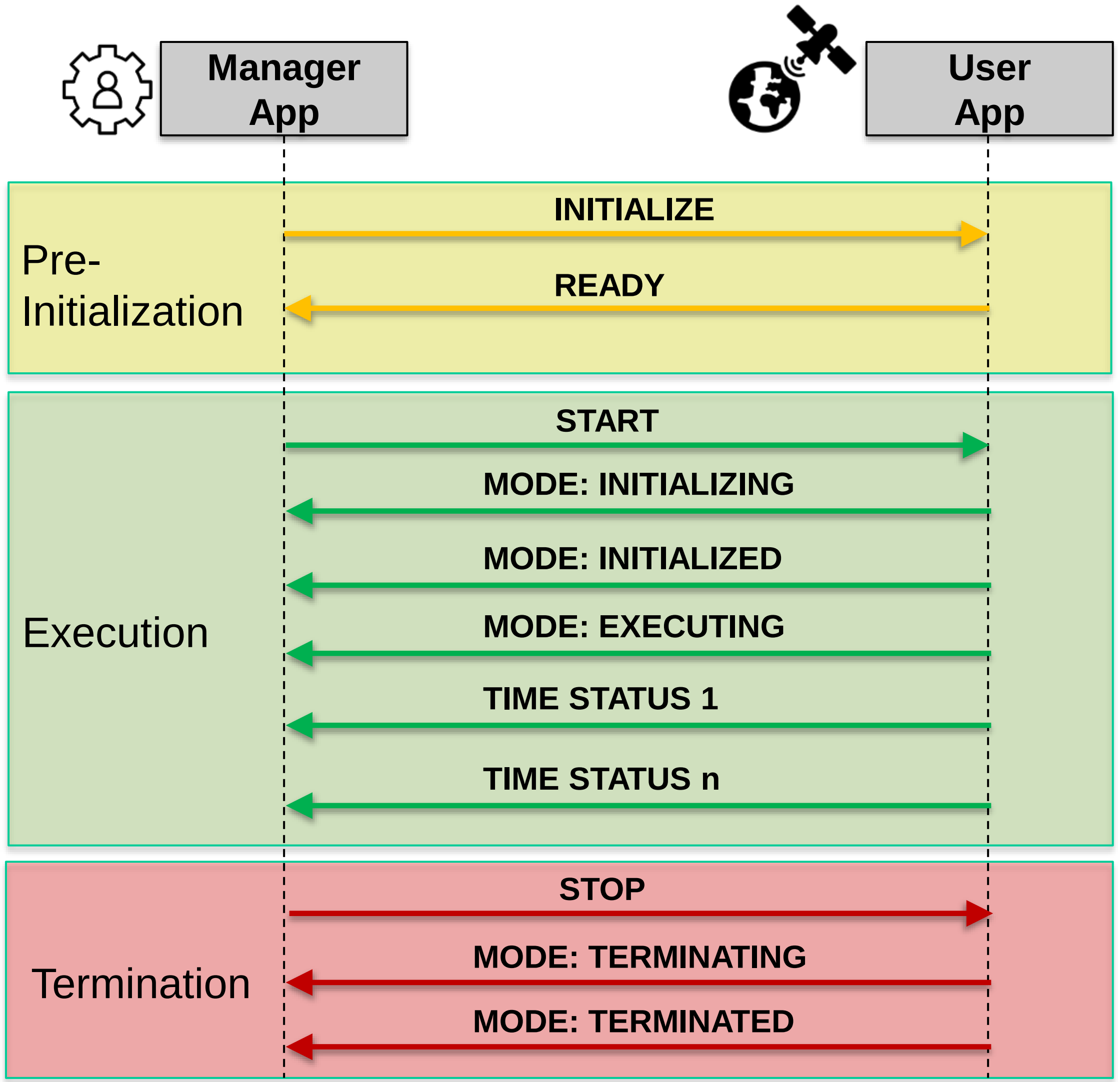
= Satellites = Fire Detected

ESTO Earth Science Technology Office

General NOS-T Interface

Manager App Messages

- **Initialize** = Start application
- **Start** = Begin Test Run
- **Stop** = Stop Test Run



User App Messages

- **Ready** = Ready to Start Test Run
- **Mode: Initializing** = App begins initialization
- **Mode: Initialized** = App is initialized
- **Mode: Executing** = App is Executing
- **Time Status** = Heartbeat
- **Mode: Terminating** = App begins termination
- **Mode: Terminated** = App has terminated run

NOS-T Tools

- Reference NOS-T interface implementation and application templates in the Python language

Simulator: precision timing loop for non-real-time applications

Manager Application: schedules test run execution commands

Application Template: wrapper for low-level MQTT protocol

Logger Application: records all test run messages exchanged

Managed Application: implements all required manager commands

Compliance Checker*: verify user application meets NOS-T req's (in development)*

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Summary of Accomplishments

- NOS-T provides an information system on which to prototype and mature NOS missions
- NOS-T Framework defines the technical interface to enable participation by disparate organizations
  - Loosely-coupled structure via an event-driven architecture
  - Information exchange based on lightweight MQTT protocol
  - Supports simulated and real-time scenario execution
  - Demonstrated with incremental application cases
- Upcoming Release of NOS-T Framework (Feb. '22)
  - NOS-T Interface Control Document (v1.0)
  - Representative NOS mission demonstration with 3+ nodes
  - Open-source release of NOS-T Tools library

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Actual or Potential Infusions and Collaborations

- Infusion:
  - NOS-T technology used in several AIST-21 proposals and NIP project: Co-simulation for Partnerships to Observe Convective Storm Systems (80NSSC21K1515; PI: Grogan)
  - NOS-T technology used in NOS Pilot (lead: Ben Smith)
  - NOS-T technology targeted for NOS-Live Pilot (lead: Mike Seablom)
- Technology transfer:
  - NOS-T Tools open-source release (BSD license) in Jan 2022
- Collaborators/Contacts:
  - NOS Pilot (ARC/GSFC/JPL/LaRC/MIT/USC), NOS-Live Pilot (GSFC/JPL/UMD), Oceans NOS (ARC/JPL), Carrie Vuyovich (GSFC), Danielle Wood (MIT)

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Publications

- P.T. Grogan, "**New Observing Strategies Testbed (NOS-T) Design and Development**," *12th Annual SERC Sponsor Research Review*, Nov. 18, 2020.
- P.T. Grogan, "**Co-Design and Co-Simulation Infrastructure for a New Observing Strategies Testbed**," eLightning Talk, *2020 AGU Fall Meeting*, Dec. 10, 2020.
- P.T. Grogan, "**New Observing Strategies Testbed (NOS-T) Design and Development**," *2021 Earth Science Technology Forum*, Jun. 10, 2021.
- P.T. Grogan, H.C. Daly, M.S. Brand, and J.J. Sellers "**New Observing Strategies Testbed (NOS-T) Architecture: Evaluating Dynamic Response to Emergent Events**," *2021 IEEE International Geoscience and Remote Sensing Symposium*, Jul. 15, 2021.
- P.T. Grogan, "**New Observing Strategies Testbed (NOS-T) Design and Development**," *13th Annual SERC Sponsor Research Review*, Nov. 3, 2021.
- B. Chell, M. LeVine, L. Capra, J.J. Sellers, and P.T. Grogan, "**New Observing Strategies Testbed for the Prototyping and Co-design of Earth Science Space Missions within a Digital Engineering Environment**," in review for *Systems Engineering* journal.

List of Acronyms

API	Application Programming Interface
BSD	Berkeley Source Distribution
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
NOS	New Observing Strategies
NOS-T	New Observing Strategies Testbed
TLS	Transport Layer Security
VIIRS	Visible Infrared Imaging Radiometer Suite

D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions

Sreeja Nag (PI, NASA Ames Research Center/BAER Institute)
Mahta Moghaddam (co-I, University of Southern California)
Daniel Selva (Co-I, Texas A&M University)
Jeremy Frank (co-I, NASA Ames Research Center)

AIST-18-0086 Annual Technical Review
January 2022

Team listing: Vinay Ravindra (ARC/BAERI), Richard Levinson (ARC/Wyle), Ruzbeh Akbar (MIT), Amer Malebari (USC), Archana Kannan (USC), Ben Gorr (TAMU), Alan Aguilar (TAMU)

D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions

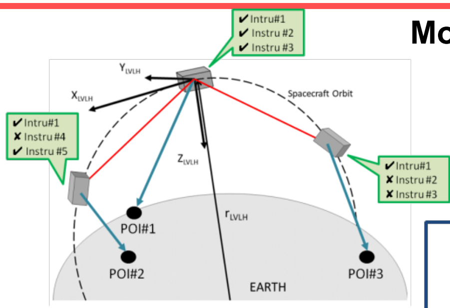
PI: Sreeja Nag, NASA Ames Research Center and BAER Institute

Objective

Develop an operations design tool that will, for a given distributed space mission (DSM) architecture:

- plan re-orienting and operations of heterogeneous payloads
- account for power/payload constraints
- maximize science value using an iterative science observable simulator based on Observing System Simulation Experiments (OSSEs) adapted for real time planning and rapid mission design

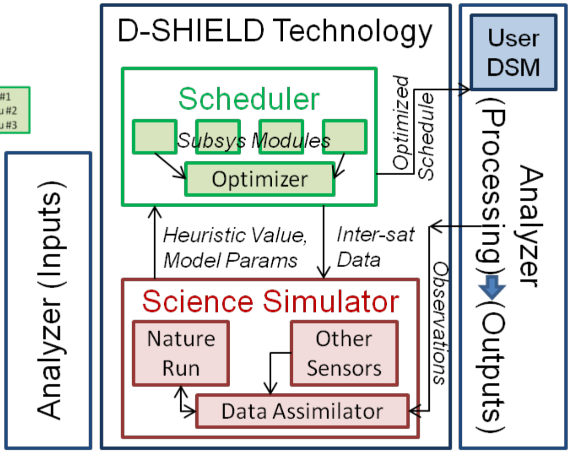
This project contributes to the New Observing Strategy (NOS) thrust area by developing an AI-based planning and scheduling-based DSM operations tool



(above) Cartoon of 3-satellite constellation with multiple instruments and D-SHIELD coordinated decisions

(right) D-SHIELD system diagram including data flows.

Modular Technology and Assessment:



Approach:

- Build an intelligent scheduler that can run on the ground in a centralized way or onboard multiple spacecraft in a distributed manner
- Build an observable science simulator enabling scheduler decisions and science performance comparisons.
    - Baseline simulator will model soil moisture scenarios
    - Project developments will enable applications to other responsive remote sensing (e.g. fires, cyclones).
- Build an operations tradespace analyzer to evaluate system performance and inform trade-offs such as running onboard vs. offline
- Integrate system; apply to soil moisture uncertainty reduction globally

Key Milestones

• Optimization Algorithms study completed	07/20
• Payload Module developed	10/20
• Active MW Simulator developed	10/20
• Power Module dev, integrate w/ current modules	10/20
• Operations tests developed	01/21
• Hydrologic land-surface model developed	03/21
• Scheduler Optimizer developed	07/21
• Scheduler and Science Sim. Modules integrated	10/21
• Full system integrated with Analyzer	05/22

TRL_{in} = 2 ; TRL_{now} = 3

Co-Is/Partners: J. Frank, ARC; M. Moghaddam, USC; D. Selva, Texas A&M University

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Background and Objectives

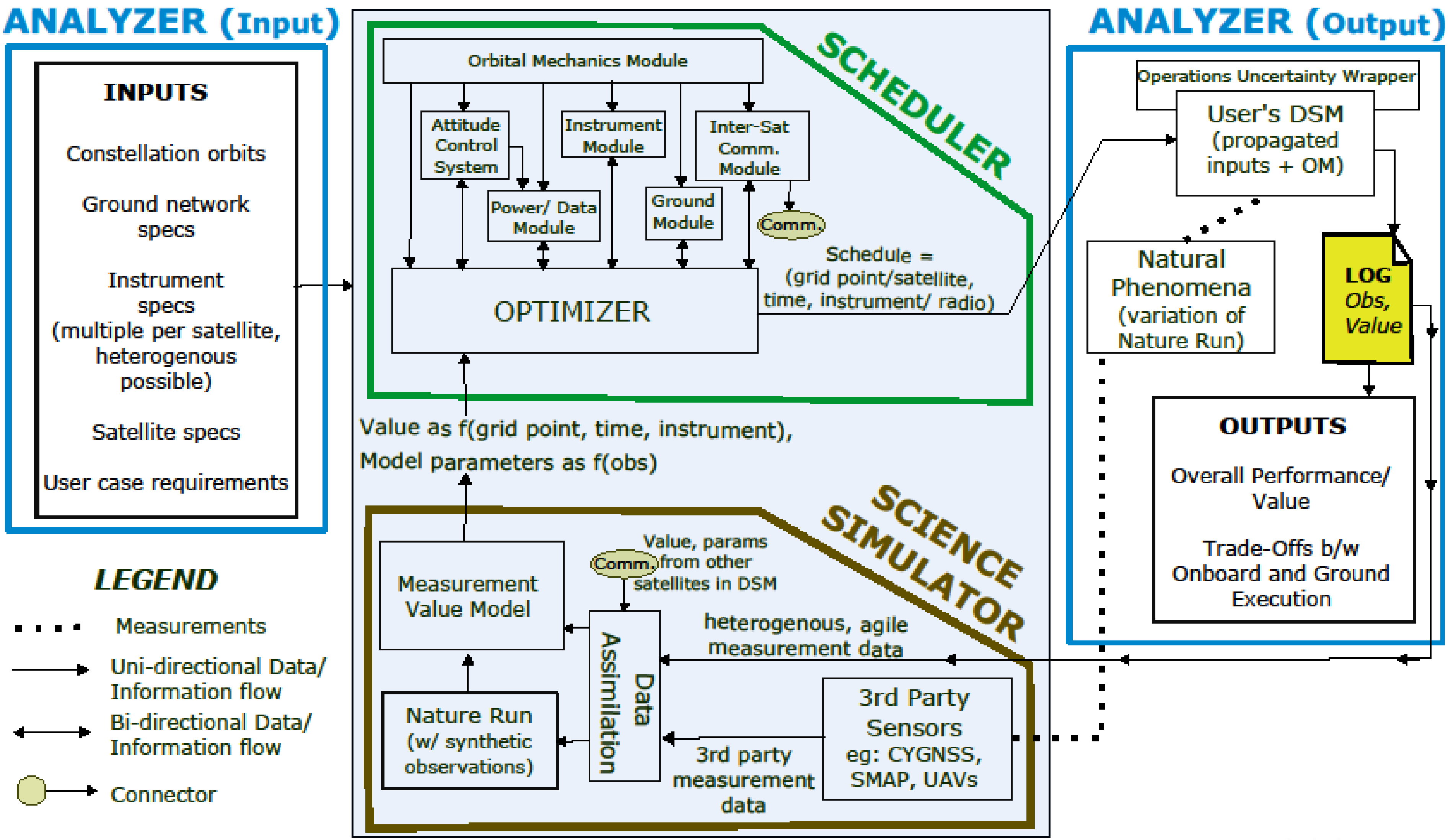
Technology and science gap that requires this project.

- SCIENCE: Science assimilation, prediction, planning in the loop autonomous constellations with agile pointing have never been demonstrated
- SCIENCE: Physics-based numerical models have been used to train machine/deep learning (ML/DL) architectures but they have never been used as automated OSSEs for real-time planning.
- TECH: Individual components have been developed and published; But adapting these for automated constellation scheduling with coordinated, re-orientable satellites using a real-time updated science value function has never been demonstrated
- TECH: Data downlink scheduling from constellations are available; BUT tools are optimized for just that, and not for command and control (C2) of better observations and science for multi-satellite missions.

Objectives of this project.

- D-SHIELD solves for the above gaps and provides automated tools for operations design and planning that allow for **efficient fleet management**.
- Relevant Areas: Water & Energy, Disasters

Background and Architecture



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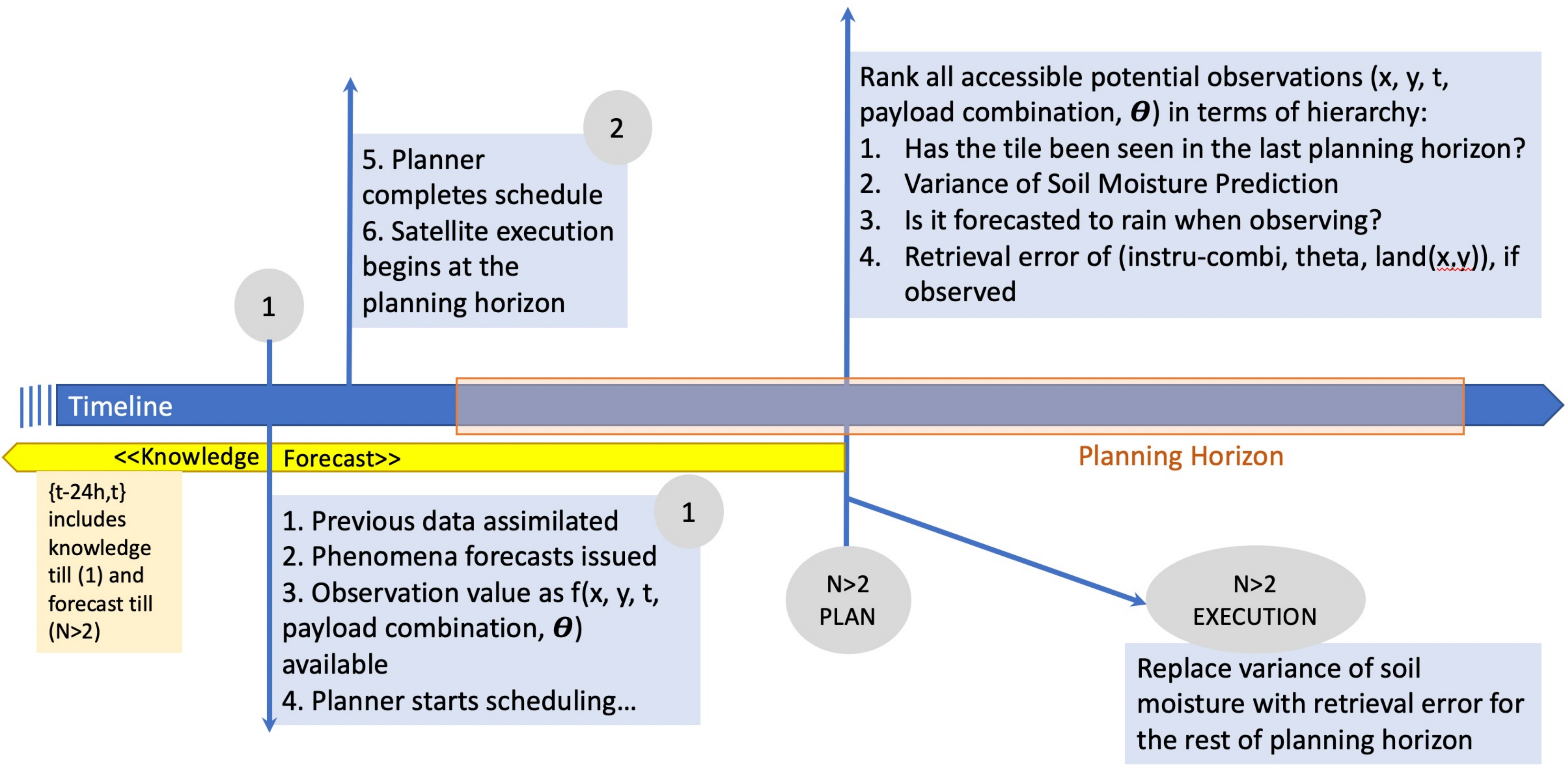
Summary of Concept of Operations

Planning Ops using (dynamic) knowledge and forecast of soil moisture and precipitation, that is sensitive to Season, vegetation, soil types (static)



Summary of Science Advancements

For D-SHIELD: The scientific value of making a measurement of a ground point (GP) at a given time point (TP) as a function of the biased standard deviation (SD) of the soil-moisture prediction at that GP at TP.

We **hypothesize** that targeted, good quality observations of locations and times of higher uncertainty will serve as better inputs to prediction models and improve predictive output of augmented products.

We **test this hypothesis** using [1] an example custom constellation that maximizes observation opportunity while minimizing cost, [2] customized soil moisture specific instruments, [3] an intelligent planner, and [4] a science simulator in the loop to inform the planner.

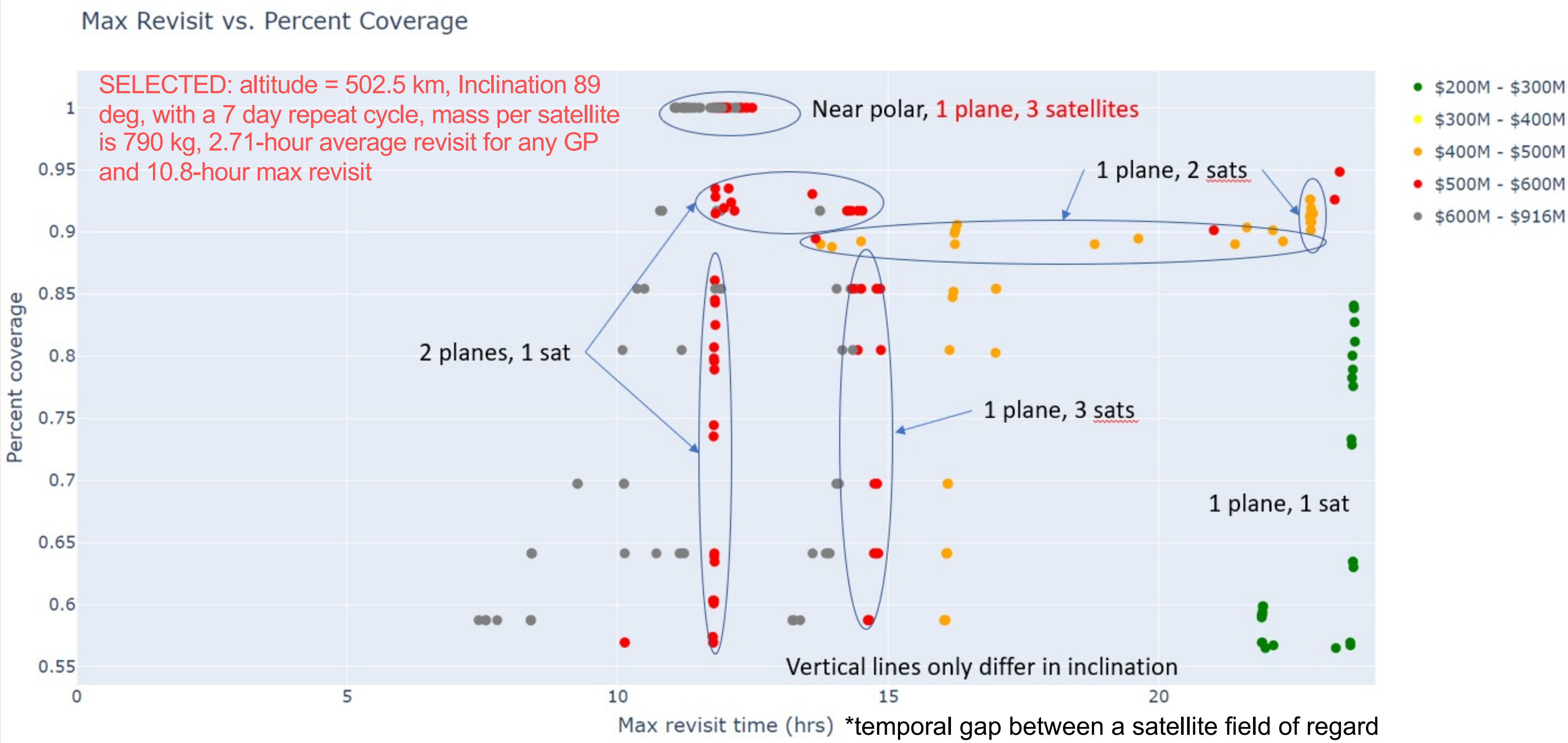
D-SHIELD (or distributed missions with intelligent observations) can be used to perform targeted high-quality imaging to *augment these global data products*. GPs are the centroid of *relevant* SMAP 9km-tiles.

	Example of a ground-based targeted observing strategy enabled by D-SHIELD	Example of a single large class observing strategy
Evaluated architectures	3 satellites in Homogeneous Walker constellation with L, P-band SAR (stripmap mode)	SMAP L-band radar and radiometer (conical-scanning mode)
Cost	$620 million, evaluated using VASSAR[37]	$915 million
Agility	Agile pointing of satellite/payload system to image targets from 30 deg to 60 deg incidence angle.	Continuous imaging of land mass covered by wide swath scans
Observations	Targeted *high-quality* observations of GPs with higher predicted soil moisture SD: 2.6E-2 m^3/m^3 compared to the global average 1.6E-2 m^3/m^3	Non-targeted observations post-processed with Sentinel SAR to produce periodic global products
Nominal instrument performance	L-Band SAR: <-30dB NESZ, 25km fixed-swath, 500 looks per km^2 P-Band SAR: <-30dB NESZ, 50km fixed-swath, 5200 looks per km^2	<-30dB NESZ, 1000 km swath. 10 looks per km^2
Soil moisture retrieval performance	1.9-4 to 1.5E-2 m^3/m^3 depending on instrument parameters using combined retrievals from multiple instruments at diff. incidence angles, polarizations	4E-2 m^3/m^3 using the same retrieval algorithms as D-SHIELD's science simulator (bias 0.023)
Predictive value over 72h	6.7k m^3/m^3 total prediction SD over 260k observed GPs (Details in *Application Readiness Plan*, p.17)	27.2k m^3/m^3 over 1.7mill GPs, using global average prediction SD

Selected Constellation Architecture and Cost

The VASSAR (Value assessment of system architectures using rules) software suite was used to identify optimum heterogeneous constellations carrying the custom instrument suite.

The baseline radar constellation was selected from the Pareto front between maximum revisit time and percentage coverage of areas of interest for soil moisture.

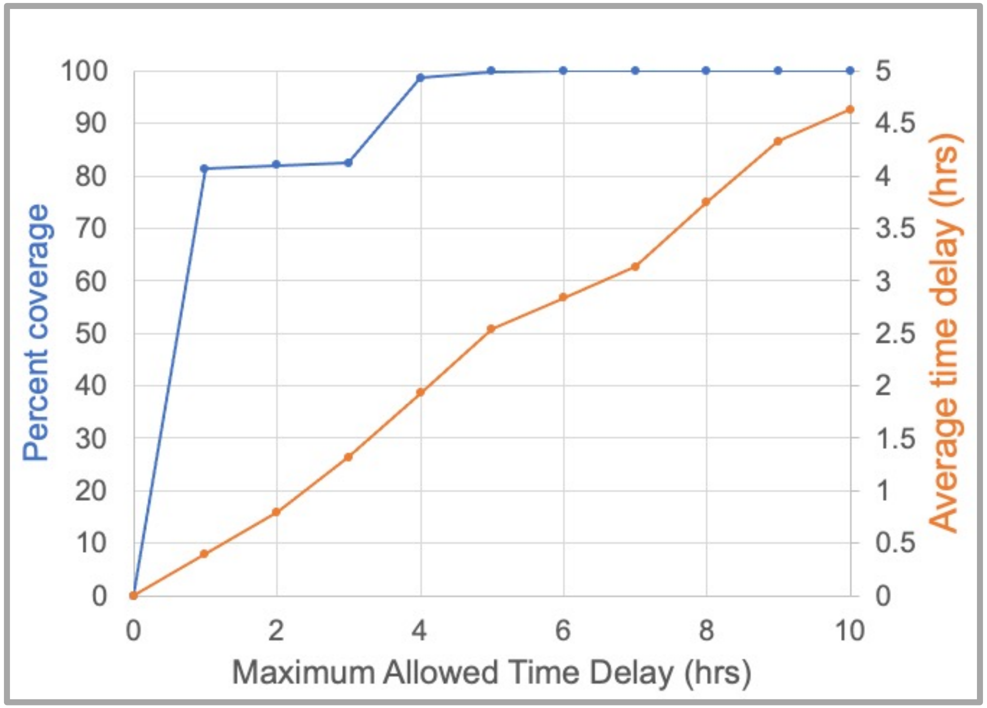


*temporal gap between a satellite field of regard accessing any GP of interest

Selected Constellation Architecture and Fusion Capability

Even a fully loaded constellation of small (16) and medium (3) sized satellites with 5 instrument types was found to be cheaper than SMAP.

To combine radar and radiometer measurements, we would like observations to be temporally close because the longer the delay between the two collections, the less physically correlated the observations are.

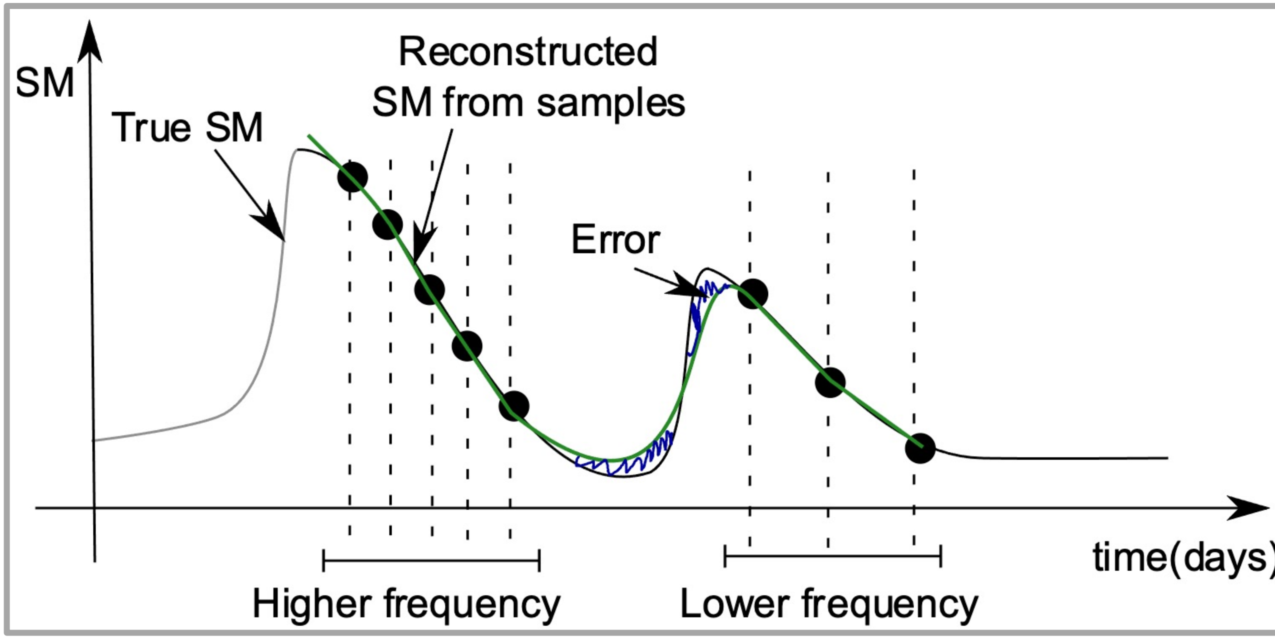


Therefore, Depending on the science assimilation constraints, a heterogeneous constellation provides the flexibility of joint inversion of data from various instruments in space (and even ground).

Science Simulator to inform the Planner Objective

Benefit of near real time retrieval, data assimilation, and prediction to inform the planner of the value of the next measurements:

When soil moisture changes rapidly (e.g. precipitation), higher frequency measurements are needed to keep the model error low, compared to times of slow changes.



*Model error is the bias-corrected difference between soil moisture **prediction** standard deviation (SD) and retrieval **measurement** root mean square error (RMSE) => Planner Objective*

Science Simulator: Soil Moisture Prediction

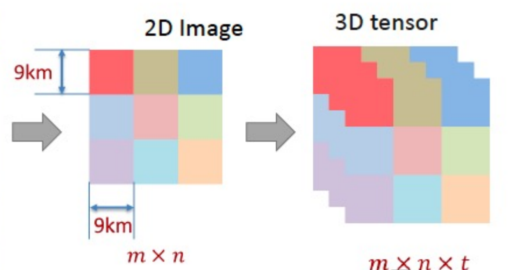
Prediction SD per GP and time step is obtained using a **convLSTM model** that is a function of soil type, vegetation, season, solar conditions, precipitation, and soil saturation. For the 3-sat baseline SAR constellation, the planner selected GPs with an average SD that is ~2x the average global SD, i.e., it targeted regions with most uncertainty.

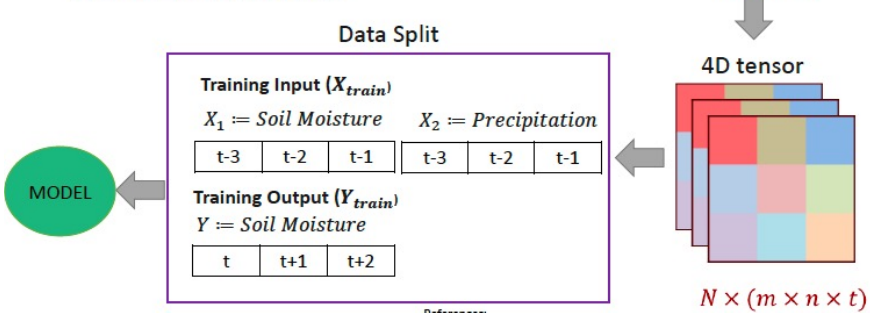
3. Data and pre-processing

Soil Moisture Active Passive (**SMAP**) L4 data
Spatial resolution: $9km \times 9km$
Temporal resolution: 3 hours

NSIDC SMAP SOIL MOISTURE ACTIVE PASSIVE

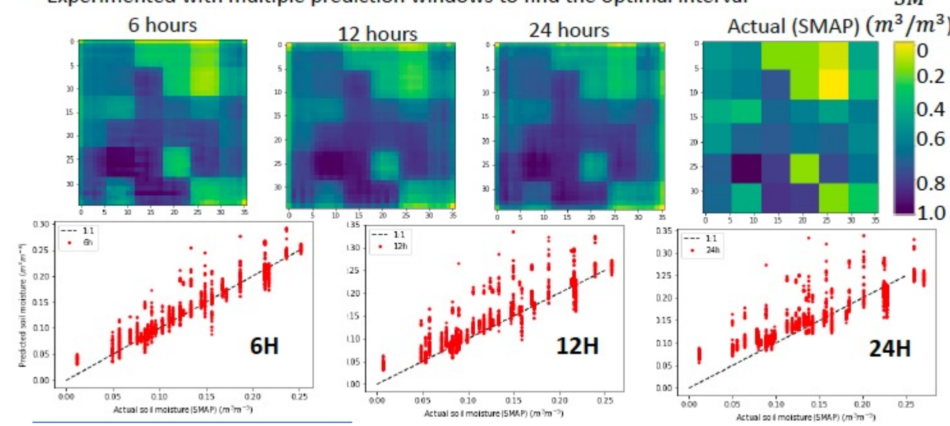
Lat	Long	SM
49.4876	-124.87	0.23311
49.4876	-124.777	0.355455
49.4876	-124.684	0.345821
49.4876	-124.59	0.355642
49.4876	-124.497	-9999
49.4876	-124.404	0.239824
49.4876	-124.31	0.216903
49.4876	-124.217	0.233664
49.4876	-124.123	0.239641



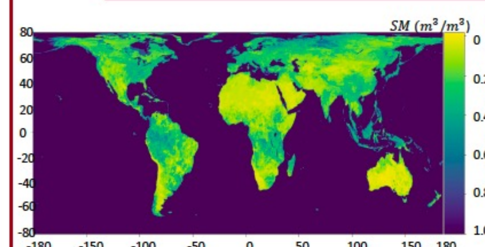


5.Choosing prediction interval window

- Experimented with multiple prediction windows to find the optimal interval



6. Forecast results



Location	Biome type	RMSE	Bias
Walnut Gulch, AZ	Shrubland	0.0348	0.0067
Tonzi Ranch, CA	Woody savanna	0.0544	0.0086
Metiolius, OR	Evergreen forest	0.0429	0.0043
Las Cruces, NM	Bare surface	0.0363	0.0093

The adjacent figure shows a predicted soil moisture image by the convLSTM model for a single timestamp

Output = SM and Variance as a function of space and future time

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Science Simulator: Soil Moisture Retrieval

Measurement error is a function of the instruments and their parameters used to make a/multiple measurements, and biome type expected (16 IGBP types into 5 major groups)

The baseline constellation shows a mean RMSE of 0.0015 across all IGBP biome types and instrument parameters, **28x compared to SMAP**, i.e., it can make significantly higher quality measurements due to custom instruments with operational agility.

Planner results show a post-observation SD of soil moisture estimates to be **~50% of the initial predictive SD**, i.e. the planner is able to half the unbiased RMSE (root of variance) across all horizons and all satellite numbers.

A few rows among thousands of combinations of instrument parameter choices (frequency band, number of observations, look angle – coded as keys in the left panel) for L and P band SARs mounted on 2 satellites – for one major biome group.

Table B Coding:

Code	*Meaning*
0	No operation
1	35+/-5 deg inc, 1 obsvs
2	45+/-5 deg inc, 1 obsvs
3	55+/-5 deg inc, 1 obsvs
4	35+/-5 deg inc, 2 obsvs
5	45+/-5 deg inc, 2 obsvs
6	55+/-5 deg inc, 2 obsvs
7	35+/-5 deg inc, 45+/-5 deg inc
8	35+/-5 deg inc, 55+/-5 deg inc
9	45+/-5 deg inc, 55+/-5 deg inc

Table B-A1 for Shrublands

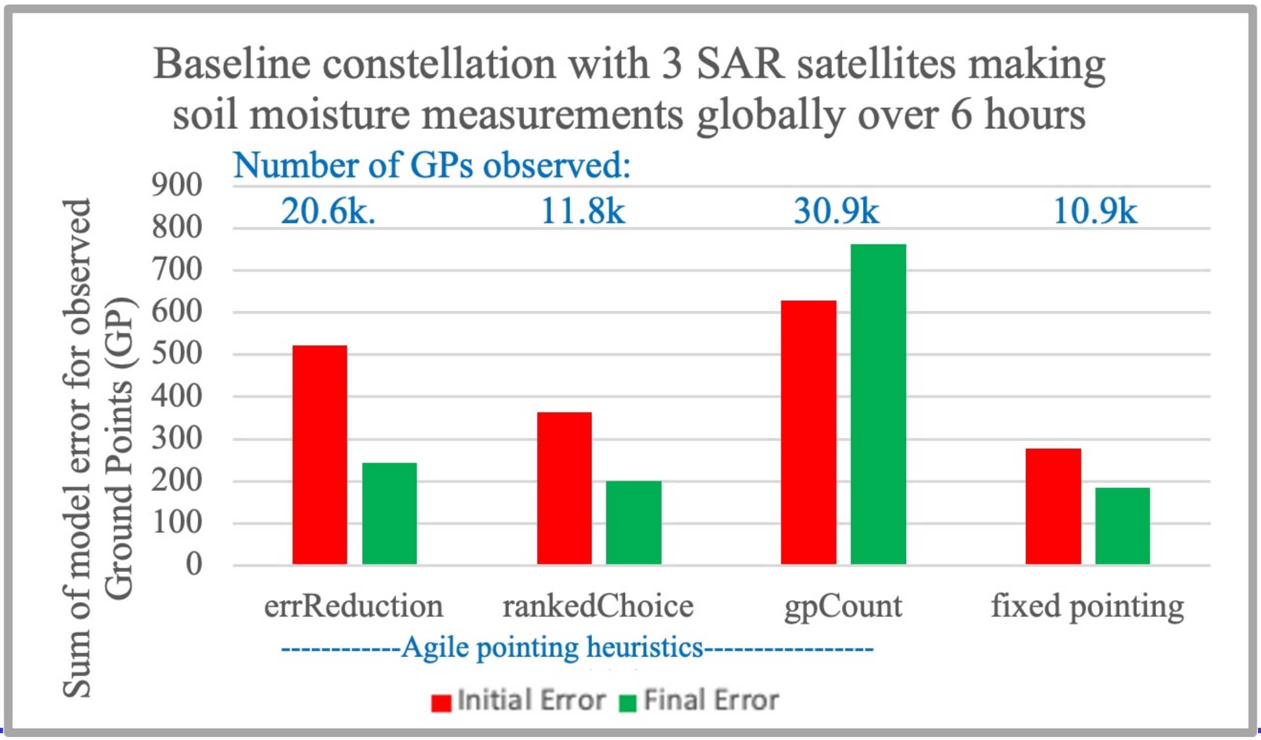
Instru #1	*Instru #2*	*Instru #3*	*Instru #4*	*RMSE*
0	0	0	0	0.0039
0	0	0	1	0.0048
0	0	0	2	0.032
0	0	0	3	0.0038
0	0	0	4	0.0048
0	0	0	5	0.0319
0	0	0	6	0.0038
0	0	0	7	0.0041
0	0	0	8	0.0161
0	0	0	9	0.0038
0	0	1	1	0.0043
.	.	.	.	.
.	.	.	.	.

Planning and Scheduling

Algorithm: **Constraint Satisfaction Programming (CP)**

Objective: Reduction in soil moisture prediction uncertainty of GPs due to making measurements of those GPs at optimal times and with an optimized set of instrument parameters.

Results: Max GPs (30.9k) are observed with *gpCount* while the *errReduction* picks the most uncertain GPs and reduces total error the most. All planner autonomy strategies show superior science return compared to *fixedPointing* for minimum increase in cost. They also observe up to 3x more GPs compared to non-agile constellations.



Planning and Scheduling

Increasing constellation satellites or horizons planned: GP count as well as total error reduced (across all observed GPs) shows monotonic increase:

Scenario (6 hours)	# GP observed (unique)	Initial Error per GP	Final Error per GP	Total Error Reduced
s1.errReduction	7317	2.63E-02	1.25E-02	101.15508
s1+s2.errReduction	13660	2.59E-02	1.19E-02	191.45954
s1+s2+s3.errReduction	20204	2.58E-02	1.20E-02	278.71958

Scenario (all errReduction)	6-hour Horizon	# GP observed (unique)	Initial Error per GP	Final Error per GP	Total Error Reduced
sat 1 + sat 2 + sat 3	1	20204	2.58E-02	1.20E-02	278.71958
sat 1 + sat 2 + sat 3	2	23078	2.93E-02	1.30E-02	377.00407
sat 1 + sat 2 + sat 3	3	19906	2.69E-02	1.24E-02	287.28447
sat 1 + sat 2 + sat 3	4	23858	2.52E-02	1.22E-02	308.77485

*Initial error = soil moisture prediction SD, final error = measurement RMSE of the observation, both shown per GP and both computed as unbiased parameters in m^3/m^3 volumetric soil moisture units

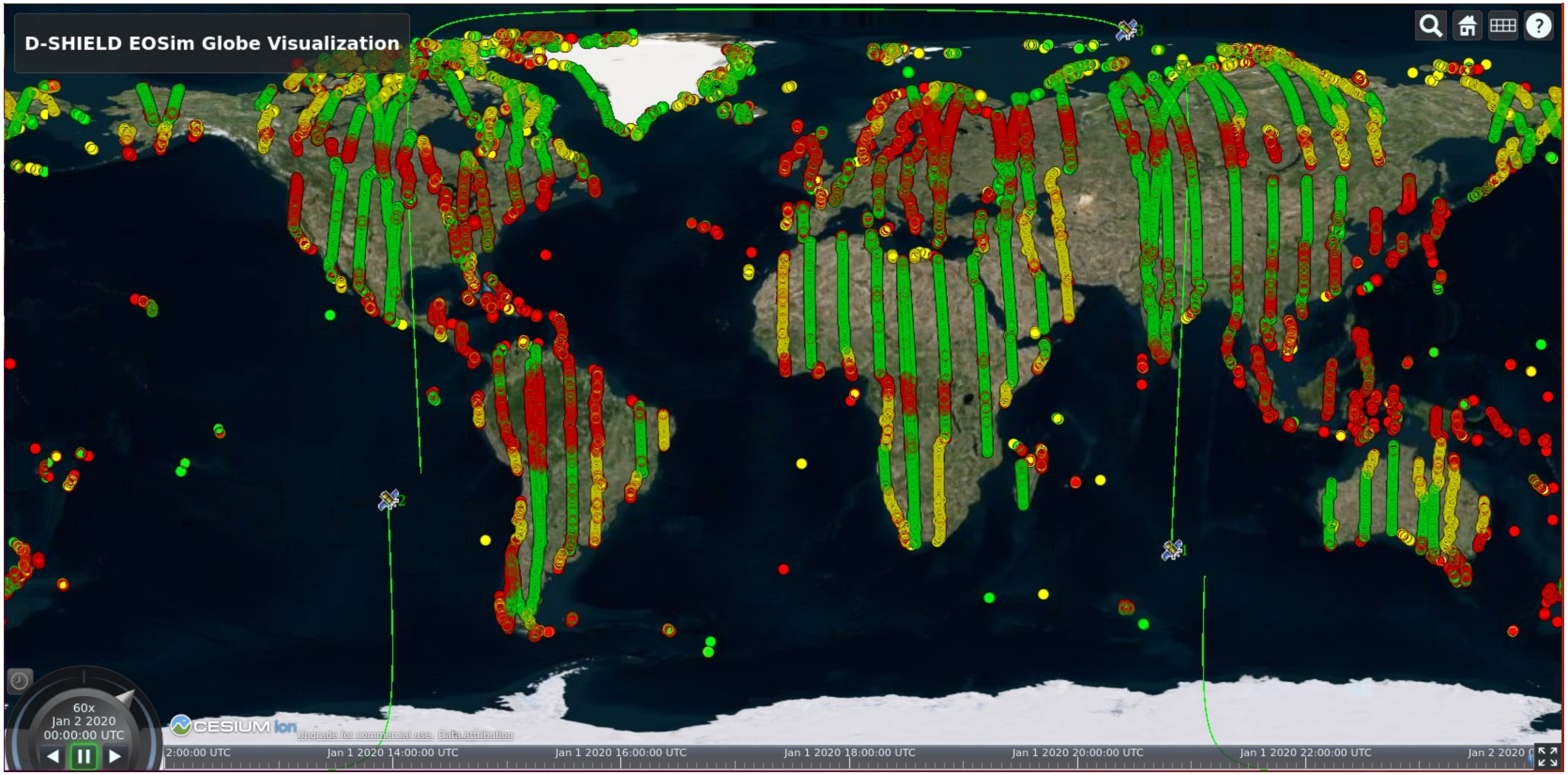
Nearly 87k GPs were observed by 3 satellites over a 24h period. D-SHIELD can smartly maneuver to maximize unique or fast-changing GPs and continue to increase coverage to ~175k GPs in 2 days and ~260k GPs in 3 days.

Exploring MILP options for optimality …

As battery+power duty cycle constraints tighten from {484Wh,266W} to {350Wh,260W} to {250Wh,266W} to {160Wh,253W}, the lowest depth of discharge the battery reaches drops from 77% to 71% to 63% to 47%.

Demo on D-SHIELD's Visualization Tool

The screenshot below shows 12h coverage (on 2D Earth) of the smart 3-sat constellation. Observation value has been normalized globally, therefore biomes corresponding to high retrieval errors are penalized in red.



Full Video available at: http://sreejanag.com/Videos/eosim_demo_3sat.mp4

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Summary of Accomplishments and Future Plans

- All modules coded and published
- Some are released open source
- Full constellation use case modeled and science benefit demo'ed

TO DO:

- Integration of the radar and radiometer modules for joint retrievals, closing the loop between prediction and retrieval
- Further optimization of the planner to use the benefits of MILP + CP, extension to include the updated science simulator
- Operational tradespace analysis for different types of constellations beyond baseline
- Update orbital coverage algorithms, release visualization tool

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Actual or Potential Infusions and Collaborations

- The D-SHIELD team has worked very closely with several R&D as well as mission teams to ensure transfer of technology to better applications:
  - Infusion => NOS Oceans Study and Demo (PI: Dr. Laura Rogers, NASA LARC)
  - Knowledge transfer => AIST's SpcTOR project (PI: Prof. Moghaddam), NOS Floods Demo (via Dr. Ben Smith and Dr. Jacqueline Le Moigne)
  - Technology transfer => Released several modules of D-SHIELD (orbitPy, instruPy, adcPy, EOsim) under the open-source Apache License 2.0 permissive license. The rest will be released by June 2022
  - Transition => Planning to prototype a subset of D-SHIELD that can use reflectometer measurements for soil moisture measurements for a demo in the CYGNSS mission

- Summary of actual or potential collaborations
  - Distributed Spacecraft Autonomy (DSA) Team via Dr. Jeremy Frank and Rich Levinson; flight demonstration of 3 cubesats in formation flight funded by STMD's GCD
  - SMAP Team via Prof. Mahta Moghaddam and Prof. Dara Entekhabi
  - CYGNSS Team via Prof. Chris Ruf
  - SNOOPI Team via Prof. Jim Garrison
  - NASA Applied Sciences (Wildfire monitoring) via Dr. Vince Ambrosia
  - USGS EROS (Earth Resources Observation and Science) Center via. Dr. Kurtis Nelson

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- Technical and Science Advancements
- Summary of Accomplishments and Plans Forward
- Actual or Potential Infusions and Collaborations
- Publications - List of Acronyms

Publications

JOURNALS

1. R. Lammers, A.S. Li, V. Ravindra, S. Nag, *"Prediction Models for Urban Flood Evolution for Satellite Remote Sensing"*, Journal of Hydrology, 603 (2021): 127175
2. V. Ravindra, S. Nag, A.S. Li, *"Ensemble Guided Tropical Cyclone Track Forecasting for Optimal Satellite Remote Sensing"*, IEEE Transactions on Geoscience and Remote Sensing (TGRS), 59 (2020), no. 5, pp. 3607-3622
3. V. Ravindra, S. Nag, *"Fast Methods of Coverage Evaluation for Tradespace Analysis of Constellations"*, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 13 (2019), 89-101

CONFERENCES (1/2)

1. A. Kannan et al, *"Forecasting Global Geophysical States using a Deep Learning Model for Spacecraft Constellation Scheduling and Planning"*, AGU Fall Meeting, December 2021
2. V Ravindra, R Ketzner, S Nag, *"EO-Sim: An open-source library for design and evaluation of space observation systems; a discussion on the software design and development",* AGU Fall Meeting, December 2021
3. Levinson, S. Nag, V. Ravindra, *"Agile Satellite Planning for Multi-Payload Observations to aid Earth Science"*, International Workshop on Planning and Scheduling for Space, Virtual Forum, July 2021
4. S. Nag, M. Moghaddam, D. Selva, J. Frank, V. Ravindra, R. Levinson, A. Azemati, B. Gorr, A. Li, R. Akbar, *"Soil Moisture Monitoring using Autonomous and Distributed Spacecraft (D-SHIELD)"*, IEEE International Geoscience and Remote Sensing Symposium, Brussels Belgium, July 2021

Publications

CONFERENCES (2/2)

5. V. Ravindra, R. Ketzner, S. Nag, *"Earth Observation Simulator (EO-SIM): An Open-Source Software for Observation Systems Design"*, IEEE International Geoscience and Remote Sensing Symposium, Brussels Belgium, July 2021
6. B. Gorr, A. Aguilar, D. Selva, V. Ravindra, M. Moghaddam, S. Nag, *"Heterogeneous Constellation Design for a Smart Soil Moisture Radar Mission"*, IEEE International Geoscience and Remote Sensing Symposium, Brussels Belgium, July 2021
7. E. Sin, M. Arcak, A. S. Li, V. Ravindra, S. Nag, "Autonomous Attitude Control for Responsive Remote Sensing by Satellite Constellations", AIAA Science and Technology Forum and Exposition (SciTech Forum), Nashville, January 2021
8. S. Nag, M. Moghaddam, D. Selva, J. Frank, V. Ravindra, R. Levinson, A. Azemati, A. Aguilar, A. Li, R. Akbar, *"D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions"*, IEEE International Geoscience and Remote Sensing Symposium, Hawaii USA, July 2020
9. V. Ravindra, S. Nag, *"Instrument Data Metrics Evaluator for Tradespace Analysis of Earth Observing Constellations"*, IEEE Aerospace Conference, Big Sky, Montana, March 2020

DISSERTATION

1. E. Sin, “*Trajectory Optimization and Control of Small Spacecraft Constellations*”, PhD Thesis, University of California Berkeley, Spring 2021

KEYNOTE TALK

1. S. Nag, *“Vehicular Robotics for Responsive Environmental Monitoring”,* IEEE International Geoscience and Remote Sensing Symposium, Brussels Belgium, July 2021, Video URL: https://igarss2021.com/Keynotes.php (starting 53:40)

ESTO Earth Science Technology Office

StereoBit: Advanced Onboard Science Data Processing to Enable Earth Science

James Carr (PI, Carr Astronautics)

Christopher Wilson (Institutional PI, GSFC)

Dong Wu (Co-I, GSFC), David Wilson (GSFC)

Marco Paolieri (USC), Matthew French (Co-I, USC/ISI)

Michael Kelly (Collaborator, JHU/APL), Ian Taras (USC/ISI)

Houria Madani (Carr), Joseph Westra (Carr)

AIST-18-0082 Final Technical Review

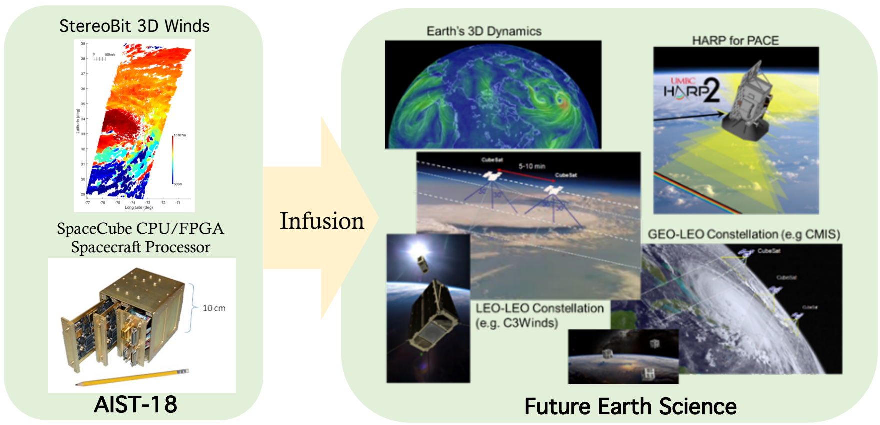
7 January 2022

StereoBit: Advanced Onboard Science Data Processing to Enable Earth Science

PI: James Carr, Carr Astronautics

Objective

- Demonstrate on-board processing to vertically resolve winds in support of high-priority Decadal Survey science.
- Enable future CubeSat/SmallSat constellation missions by:
  - Demonstrating onboard Science Data Processing on a CubeSat-type flight processor, *e.g.*, by developing StereoBit 3D Winds application on the SpaceCube hardware.
  - Demonstrating integrated operations between platforms.
  - Removing downlink bottleneck on CubeSats.
- Process and evaluate aircraft test data from Compact Midwave Imaging System (CMIS) Instrument Incubator Project (IIP).



StereoBit technology (left) can be infused into future Earth Science missions (right)

Accomplishments

- StereoBit application is now fully developed as a Core Flight System (cFS) application
  - Today it TRL 5 after end-to-end testing on SpaceCube development boards.
  - Will be TRL 6 by end of project (1/31/2022) after end-to-end testing on actual SpaceCube in lab.
- Lessons learned from StereoBit development experience recorded, shared at AGU, and will be published in IEEE.
- Science demonstrations successfully performed
  - Proxy datasets derived from MISR and GOES-R used.
  - Leader-Follower demo done with proxy datasets from Sentinel-3A and -3B SLSTR.
  - CMIS aircraft data evaluation complete with paper submitted to *Remote Sensing*.
- Lossy compression tested and evaluated for multi-angle (-platform) aerosol science applications
- Hot & Spicy Flow for Python synthesis updated and extended by end of project (1/31/2022).
- VCE extended for Global Networks, Policies, Metrics.

Co-Is/Partners: C. Wilson, D. Wu, GSFC; M. French, ISI; M. Kelly, APL

TRL_{in}= 4 **TRL_{out}= 5 (= 6 by 1/31/2021)**

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    - Science
    - Sensing
    - ***Computing***
- Technical and Science Advancements
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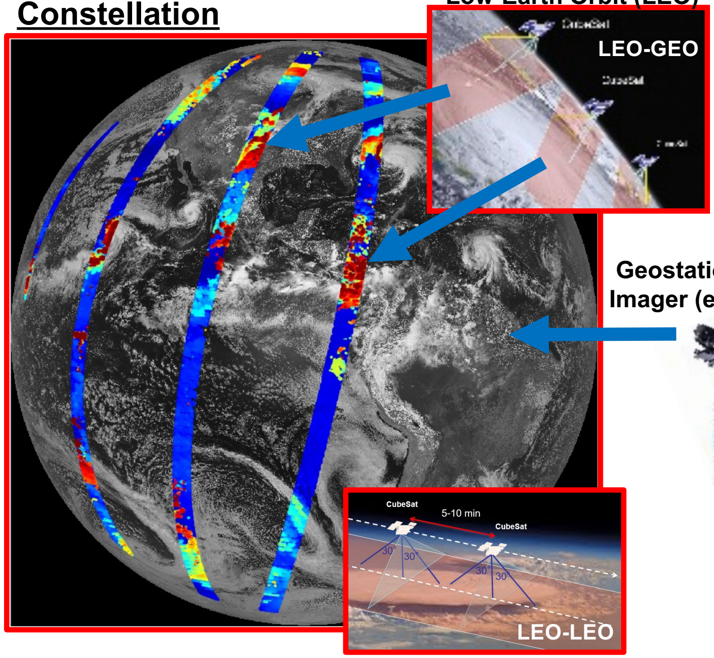
StereoBit Project Vision/Objectives

Advance Onboard Science Data Processing Capabilities within CubeSat Size Weight and Power: Develop a Specific Application for SpaceCube tied to High-Priority Decadal Survey Science

Multi-Angle, -Satellite, -Temporal Observations
Applications: Weather & Planetary Boundary Layer (PBL)

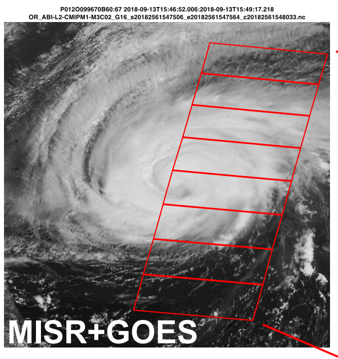
Stereo 3D-Winds Constellation

CubeSats in Low-Earth Orbit (LEO)

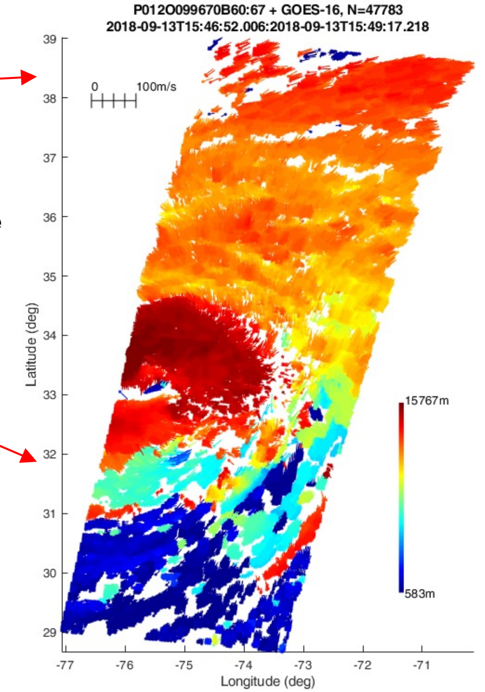


Geostationary (GEO) Imager (e.g., GOES-R)

Leader-Follower Configuration works over the Poles too



Hurricane Florence



Stereo 3D-Winds Product

- Vertically resolve winds using **Structure from Motion (SfM) stereo tracking** of clouds

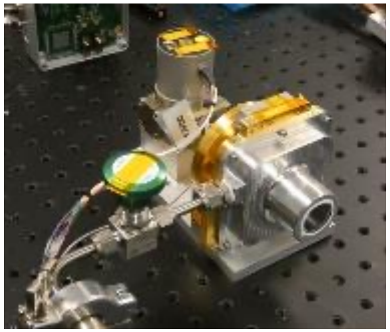
- **Integrate operations** between platforms

- Disaggregate science processing to **alleviate downlink bottleneck** of constellation architectures

- **Infuse knowledge** into the Earth Science community from our experience developing a science application on SpaceCube

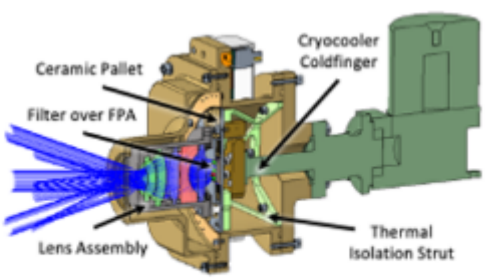
[1]Carr, J.L., D.L. Wu, M.A. Kelly, and J. Gong, "MISR-GOES 3D Winds: Implications for Future LEO-GEO and LEO-LEO Winds", *Remote Sensing*, 2019, MISR Special Issue; doi: 10.3390/rs10121885.

Compact Midwave Imaging System (CMIS)

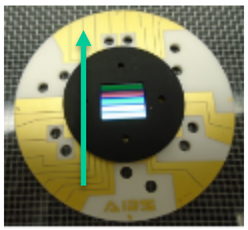


Field	Number
Multi-Spectral	2.25, 3.75, 4.05 µm
Multi-Angle	Fore, Nadir, Aft views at 3.75 µm
Weight, Power	3 kg, 7 W
Operating Temperature	150 K

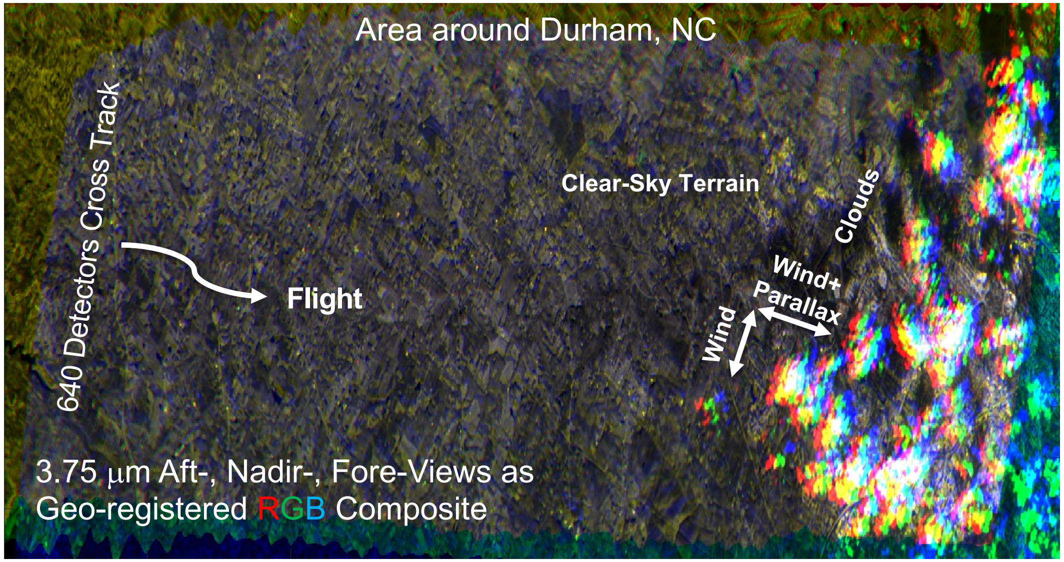
Type-2 Super Lattice (T2SL) detector



Butcher Block Filters



Recently Completed Air Campaign on NASA Gulfstream III



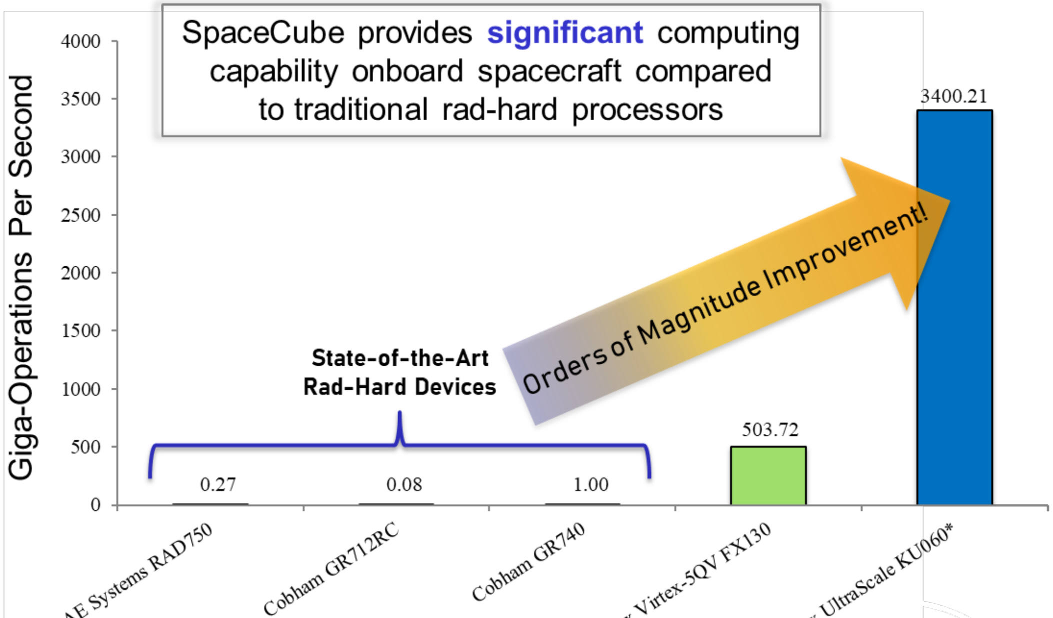
Johns Hopkins Applied Physics Laboratory

Instrument Incubator Project
PI: Dr. Michael Kelly, JHU/APL

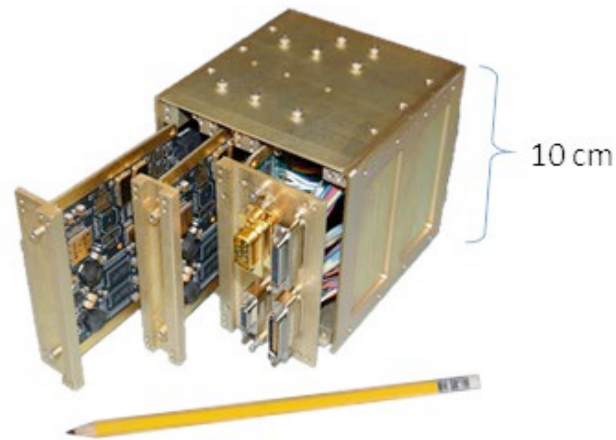
ESTO Earth Science Technology Office

SpaceCube FPGA Enabled Processor

High Compute Power to Electrical Power Ratio



Lovelly, T. M. and George, A D., "Comparative Analysis of Present and Future Space-Grade Processors with Device Metrics,"AIAA Journal of Aerospace Information Systems, Vol. 14, No. 3, Mar. 2017, pp. 184-197. doi: 10.2514/ 1.I010472



- CubeSat 1U Power-Efficient Processor
- CPU and Reconfigurable Field Programmable Gate Arrays (FPGAs)
- Mini/Mini-Z: fits within CubeSat Resource Limits
- ESTO Funded

Presentation Contents

- Background and Objectives

- Technical and Science Advancements
  - StereoBit Application
  - Developing for SpaceCube
  - Test Results
  - Virtual Constellation Engine (VCE)

- Summary of Accomplishments and Future Plans

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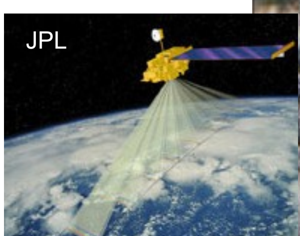
Hybrid Computing Model: Soft-Core (MicroBlaze) with FPGA Acceleration

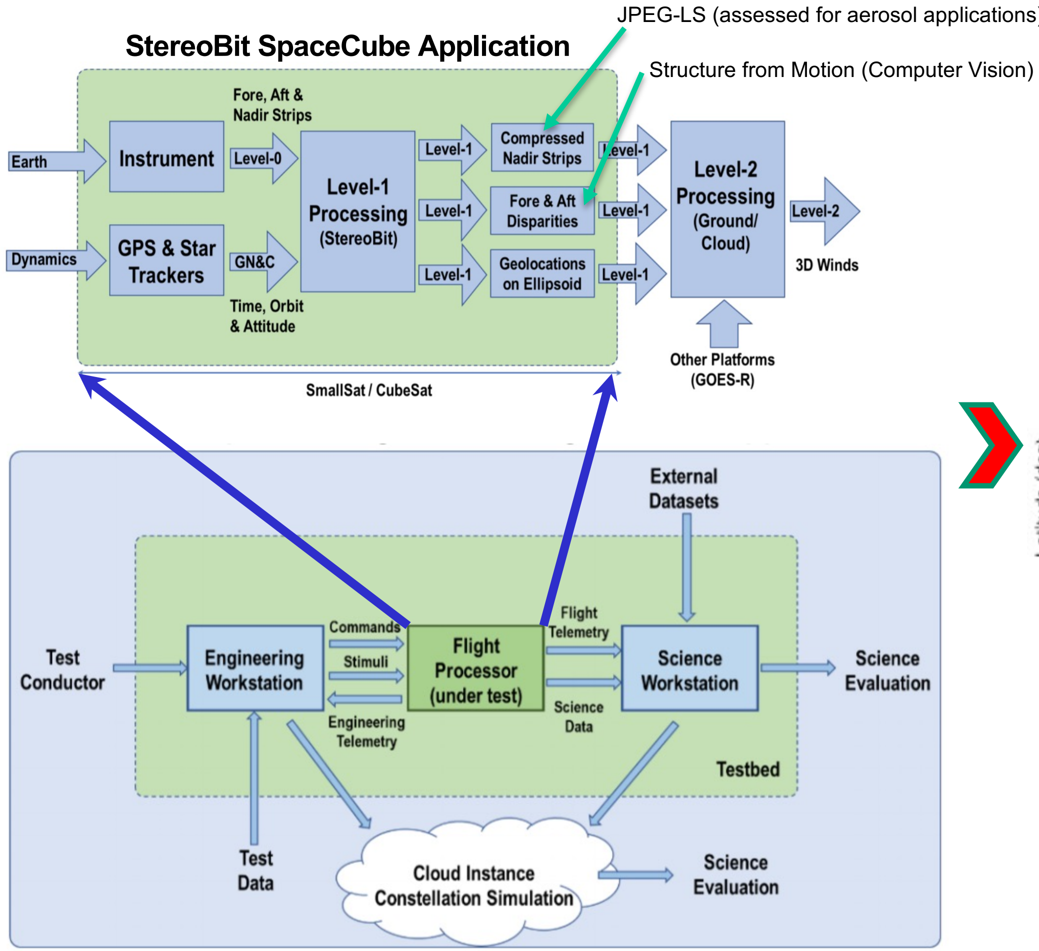
Direction of Flight

Proxy Data Simulated from MISR



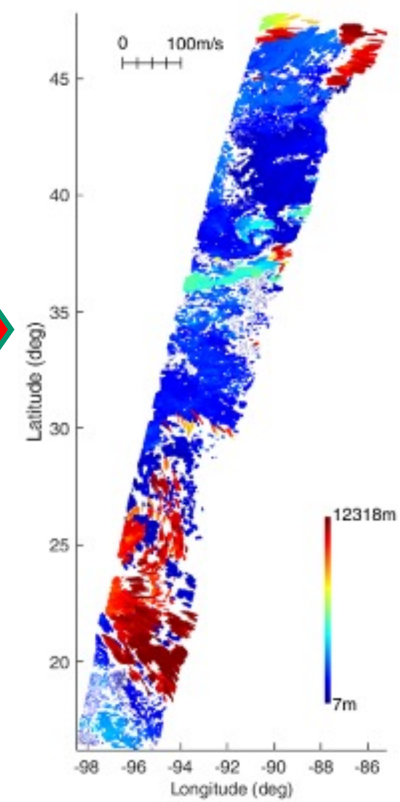
Simulated Imagery + GPS & Star Trackers

StereoBit SpaceCube Application



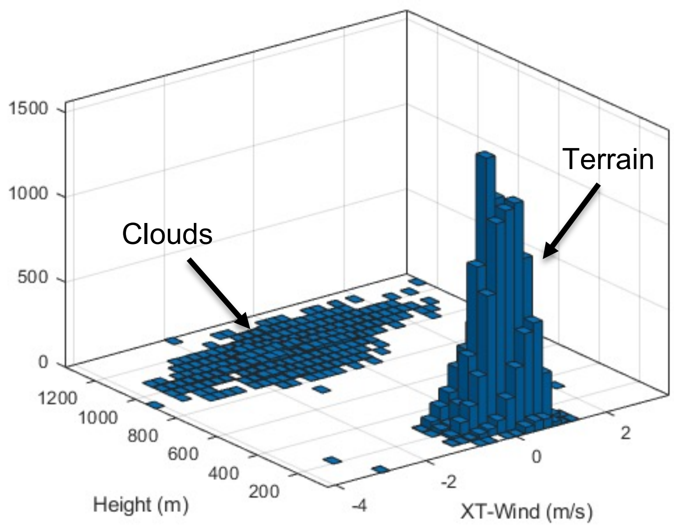
Application Development Testbed where StereoBit "flies" at GSFC

Science Product

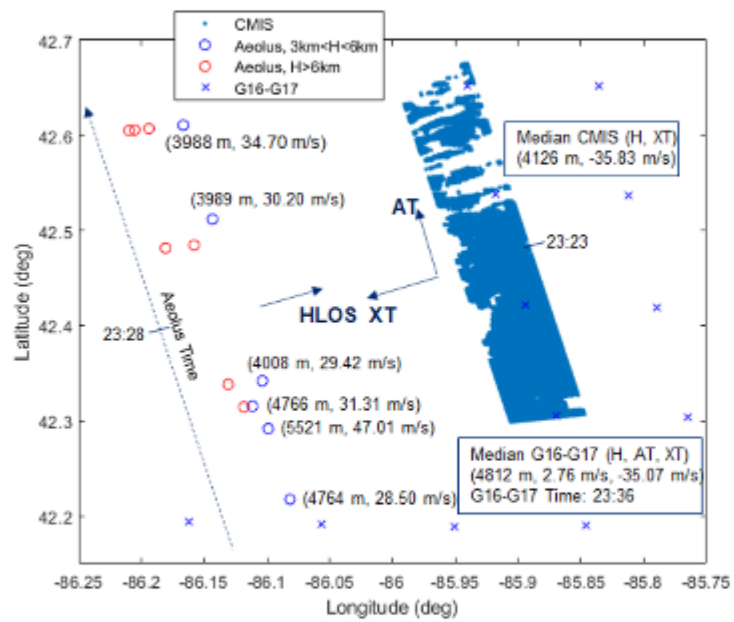


CMIS w/ StereoBit Processing

- StereoBit Pipeline processed CMIS aircraft datasets
- Validations to be published in *Remote Sensing*
  - Over clear-sky terrain vs known elevations
  - Under CALIPSO Aerosol/Cloud LiDAR
  - Under Aeolus Doppler Wi

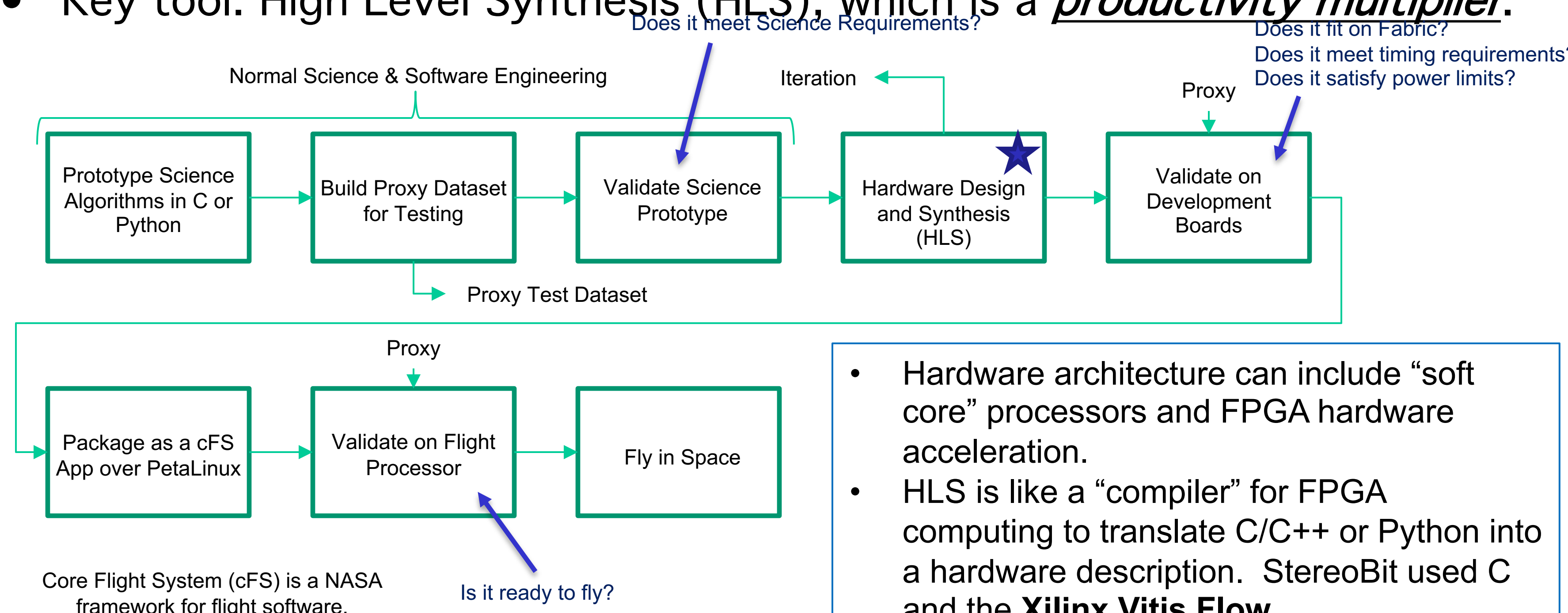


(Scene on Slide 5)



Development Approach for SpaceCube

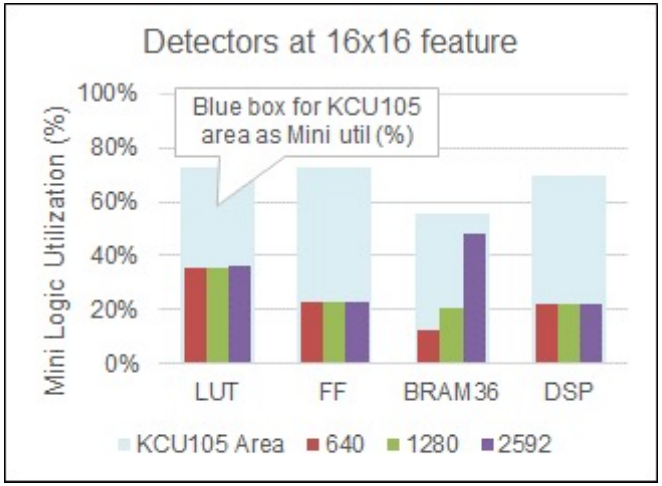
- Methods for computing on SpaceCube-like FPGA devices would be mostly unfamiliar to almost all scientific/technical teams.
- One of our goals is to blaze a trail to deliver science “Apps” for these devices and make them generally more accessible for other investigators.
- Key tool: High Level Synthesis (HLS), which is a ***productivity multiplier***.

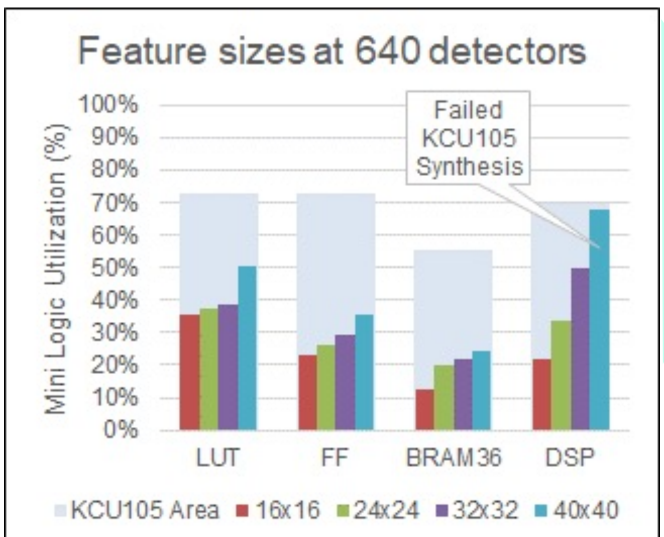


- Hardware architecture can include “soft core” processors and FPGA hardware acceleration.
- HLS is like a “compiler” for FPGA computing to translate C/C++ or Python into a hardware description. StereoBit used C and the **Xilinx Vitis Flow.**

High Level Synthesis Results

Synthesis Results Confirm StereoBit fits on Fabric

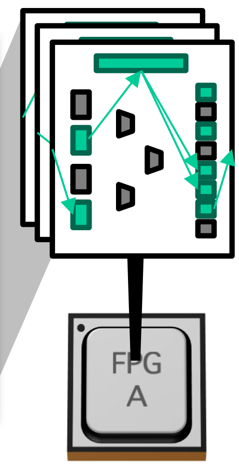




StereoBit demonstrates extensive insight into FPGA HLS (High-Level Synthesis) for advanced hardware-acceleration of science use cases and broad design-space exploration, which would be challenging or near impossible for traditional hand-coded HDL.

Case Configuration		CMIS.h Parameters				
Feature	Detectors	_feature	_stride	_scale	_searchX	_searchY
16x16	640	16	8	1.00	52	30
	1280	16	8	2.00	84	40
	2592	16	8	4.05	148	58
24x24	640	24	12	1.00	60	38
	1280	24	12	2.00	92	48
	2592*	24	12	4.05	156	66
32x32	640	32	16	1.00	68	46
	1280	32	16	2.00	100	56
	2592*	32	16	4.05	164	74
40x40	640*	40	20	1.00	76	54
	1280*	40	20	2.00	108	64
	2592*	40	20	4.05	172	82

Evaluated case configurations in terms of CMIS.h parameters
(* denotes failed KCU105 synthesis)



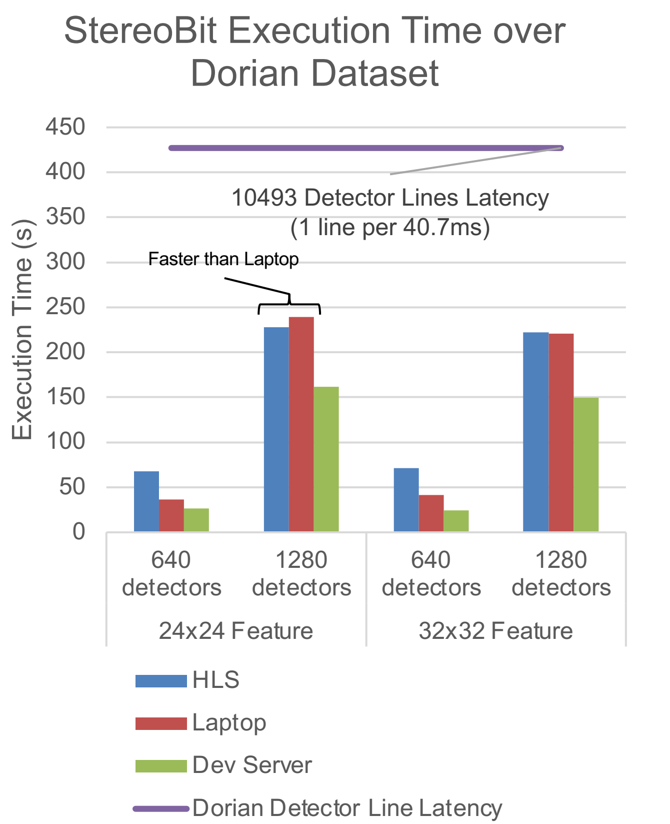
Each case represents unique synthesized and routed FPGA design for KCU105 development board

- HLS allows for rapid conversion of C/C++ Code to FPGA synthesizable HDL code alleviating some challenges from FPGA productivity
- End-to-End Flight StereoBit application completed using HLS and evaluated on hardware

ESTO Earth Science Technology Office

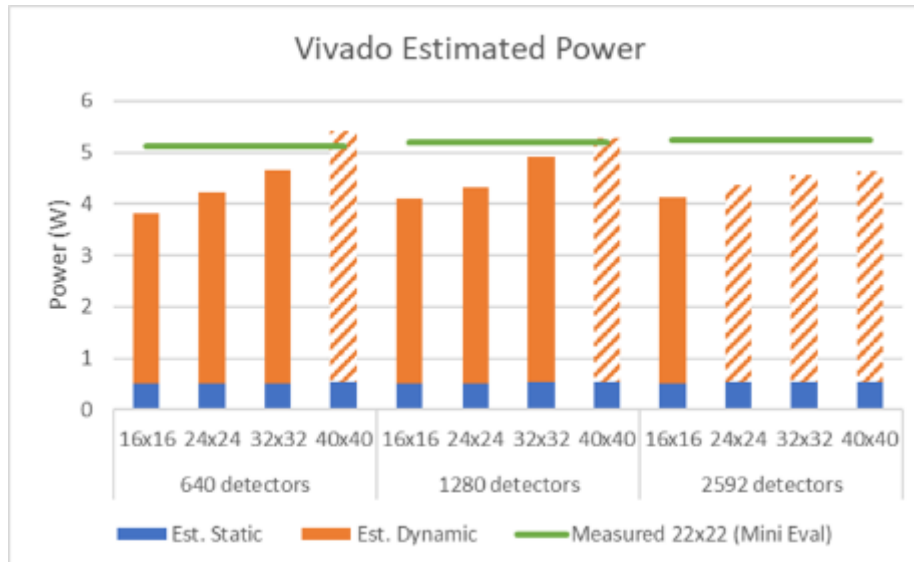
Throughput and Power Testing

Tests Prove StereoBit keeps up with Real-Time Data



Server: Intel® Xeon® Silver 4210 CPU @ 2.20GHz
Laptop: Intel® Xeon® E-2286M CPU @ 2.40GHz

Estimates and Tests Show StereoBit Power Consumption



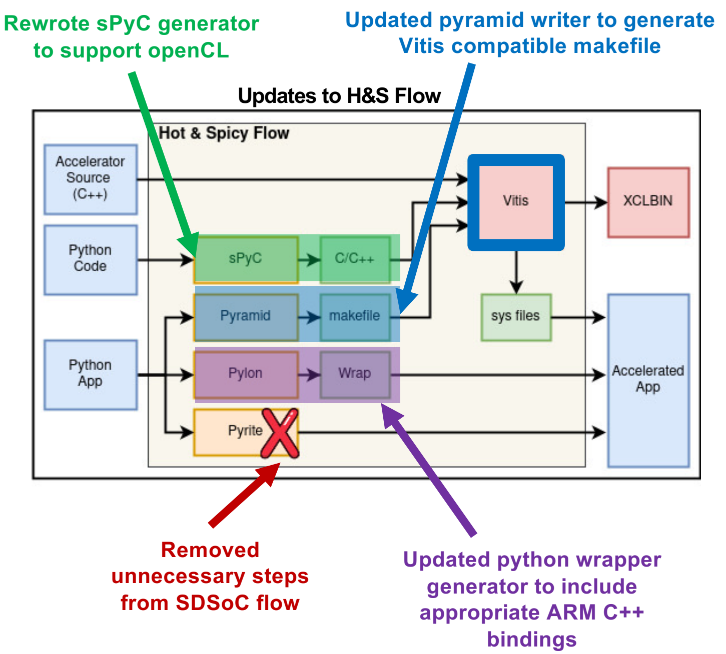
KCU105 Dev Board Tests

Measured power includes Evaluation Board overhead power

Hot & Spicy Update for Science Applications

Hot & Spicy is an AIST Legacy Capability from USC for Python High Level Synthesis

- The **Hot & Spicy (H&S)** framework is an open-source infrastructure to automate translation of Python code into HLS synthesizable C-code
  - Enables scientists and developers to more easily convert valuable applications rapidly for flight architectures like SpaceCube
- Updated Hot & Spicy toolchain to **use latest Xilinx Vitis flow** from depreciated Xilinx SDSoC environment (previously supported)
  - Updated H&S flow to generate appropriate OpenCL kernels and compilation flow
  - Automated H&S to support running applications on ARM processor architecture
  - Updates to flow are **open-sourced on Github** (https://github.com/ISI-RCG/spicy)
  - H&S flow directly compiles application on the ARM processor, speeding up compile time
- Hot & Spicy Future Plans
  - Complete H&S **MicroBlaze support** using Vitis flow
  - Continue to implement and support/update application flow running on ARM processor
  - Add automatic kernel annotation capabilities to further abstract need for hardware/ high-level synthesis domain knowledge
  - Implement Earth science toolkit consisting of common image analysis, classification, and remote sensing algorithms for benchmarking and application analysis



USC Viterbi School of Engineering

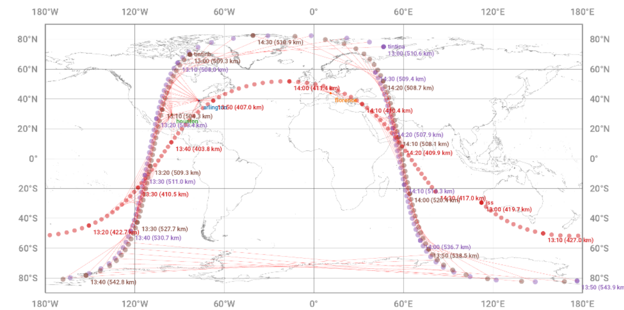
Hot & Spicy Flow Updated and Extended

ESTO Earth Science Technology Office

StereoBit Mission Prototype in VCE

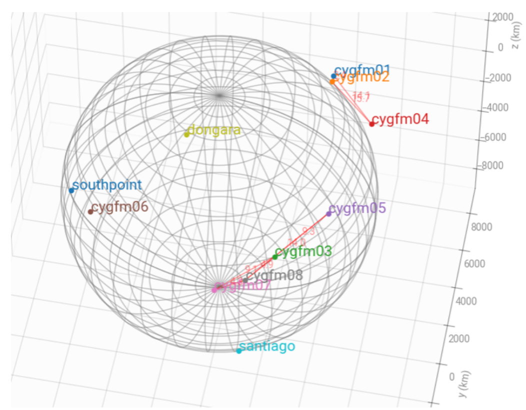
VCE is another AIST Legacy Capability from USC

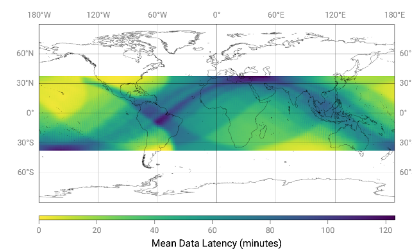
Virtual Constellation Engine: Framework to emulate satellite constellations (orbits propagation, emulation of compute/comms, collection of statistics/metrics/logs)

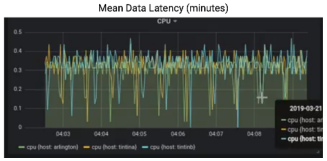


Goal: Evaluate performance metrics for different mission architectures / strategies

Added: Global Networks



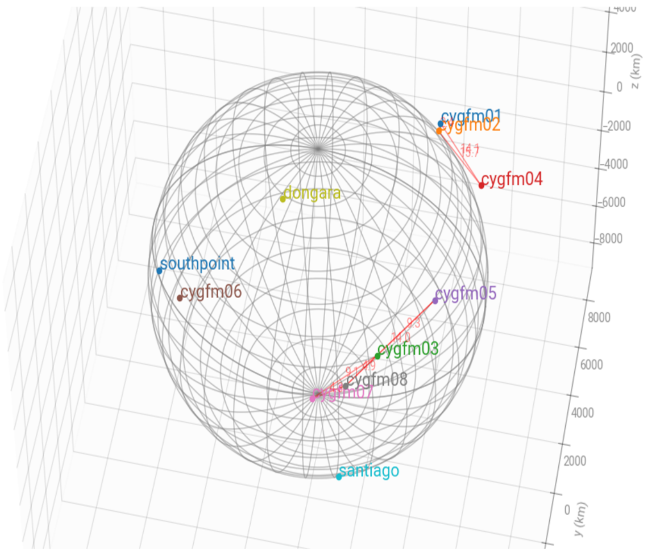


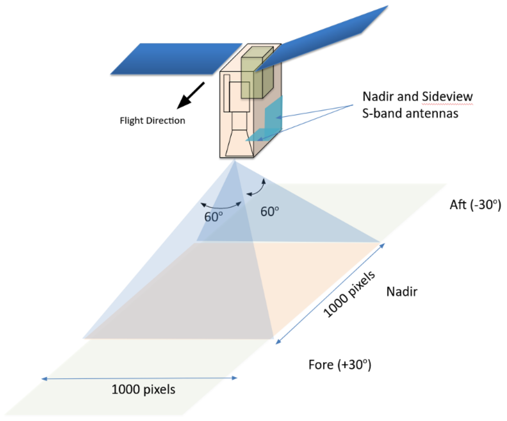


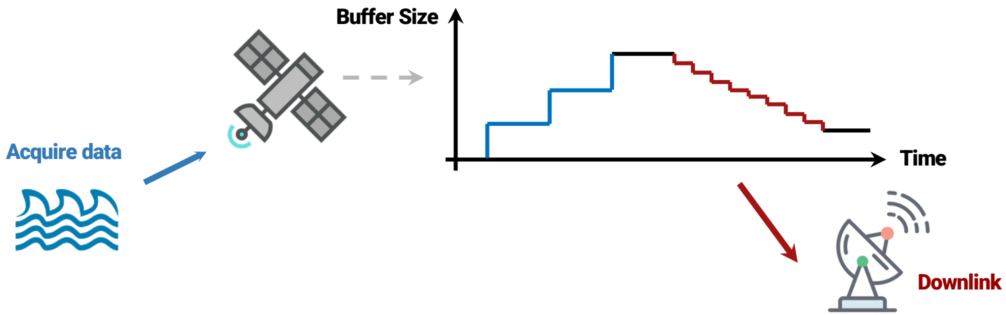
VCE upgraded for Global Networks, Policies, Metrics

Mission Concept and Metrics

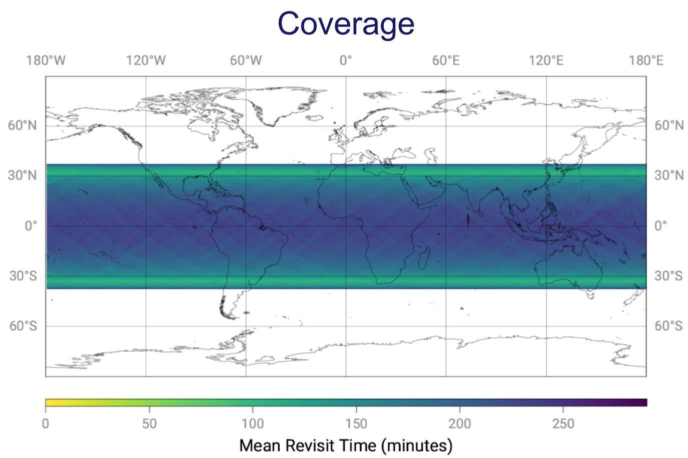
- Use **CYGNSS** as reference constellation (8 satellites, periods of 95 minutes) with NEN stations
- **Camera instrument** representative of StereoBit data volume and field of view
- **Metrics**
  - Coverage (Mean Revisit Time)
  - Latency (Time from Acquisition to Downlink)
  - Tx Buffers (On each satellite)
  - Response Time to Dynamic Events (using a global network or just the constellation)

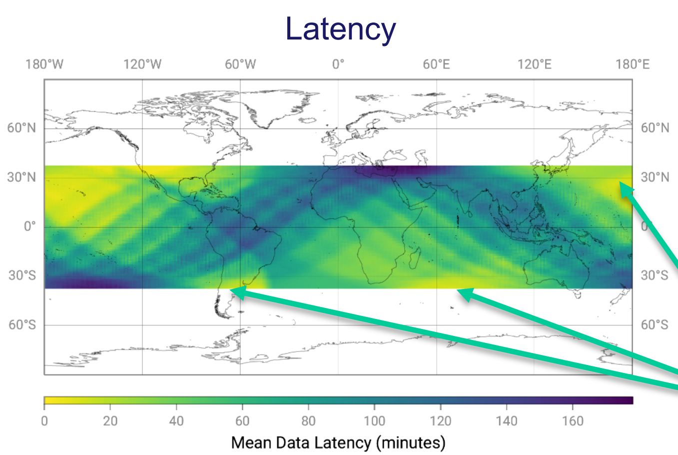


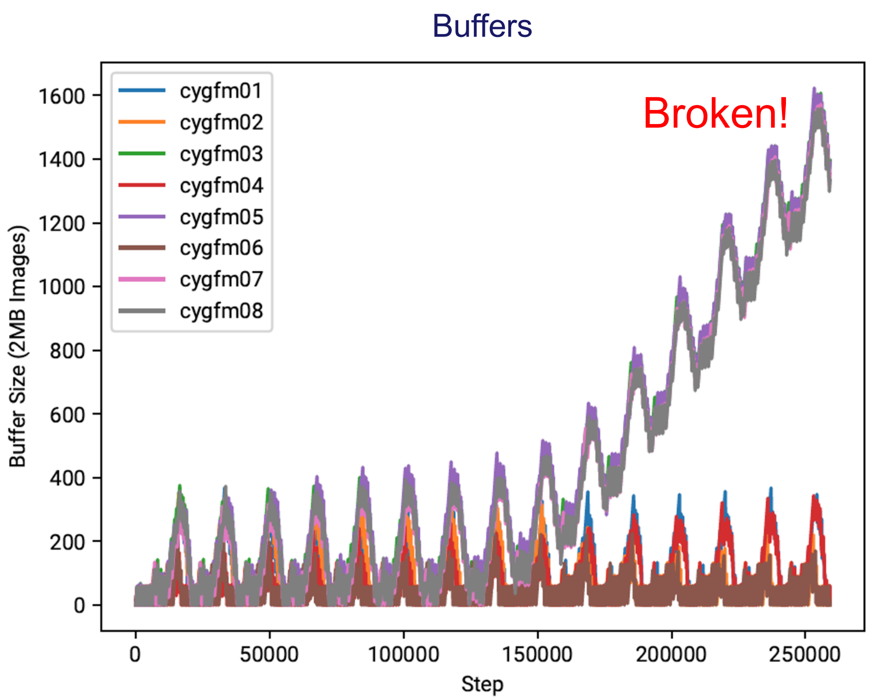




Mission Evaluation (15-day simulation)







Latency best near ground stations

Increasing buffer sizes explain data latency issues, which can be resolved with additional ground stations, priority Tx policies, or global communication networks.

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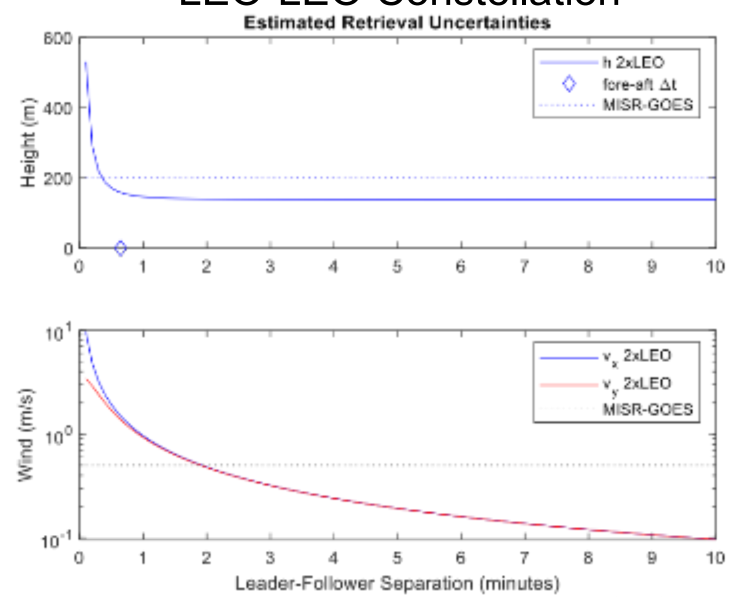
Summary and Lessons Learned

- Our StereoBit application is now fully developed as a cFS application at TRL 5.
- Lossy compression tested and evaluated for multi-angle/platform aerosol science applications (Backup)
- Lessons learned from StereoBit development experience
  - Have a mature and validated science prototype with good proxy datasets before synthesis
  - Code in a simple style and use lowest necessary precision arithmetic to conserve fabric
  - Expect inconvenience coding with transcendental functions
- CMIS aircraft testing with StereoBit code proves both.
- Leader-Follower Demo with SLSTR Proxy (Backup)

Future Plans

- Before end of Period of Performance (1/31/2022)
  - Test on SpaceCube Mini flight hardware in the testbed at GSFC to achieve TRL 6.
  - Complete Hot & Spicy flow for Python synthesis
    - Updated for Vitis
    - Extended for MicroBlaze.
  - Complete VCE investigations.
- *Remote Sensing* and IEEE journals soon.
- Longer term goals
  - NOS-T Demonstration
  - StereoBit/CMIS Flight Opportunity

LEO-LEO Constellation



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Actual or Potential Infusions and Collaborations

- Summary of actual or potential infusions
  - Infusion = CMIS Instrument Incubator Project has benefited by StereoBit Pipeline processing of its flight test data collected from the NASA Gulfstream III
  - Knowledge transfer = Path blazed by StereoBit is generally applicable across developments for all SpaceCube (or similar devices); IEEE paper will be the primary dissemination mechanism for this knowledge
  - Technology transfer = Hot & Spicy flow for Python synthesis and VCE are on Github (https://github.com/ISI-RCG/spicy and /vce)
  - Transition = Methods for FPGA acceleration are potentially transferrable to many supercomputing applications (weather forecasting, block chain, etc.).

- Summary of actual or potential collaborations
  - Future Earth Venture Program: StereoBit enables global atmospheric winds observing from a CubeSat or SmallSat constellation with multi-angle sensing capabilities (e.g., CMIS instrument). Collaboration with the CMIS team led by Dr. Michael Kelly at JHU/APL has been ongoing for several years. Parameters for a CMIS/StereoBit mission are discussed in the pending *Remote Sensing* paper: "Compact Midwave Imaging System: Results from an Airborne Demonstration" Kelly, M., J. Carr, D. Wu, A. Goldberg, I. Papusha, R. Meinhold.
  - Future Application to Operational Weather Programs: Possible applicability to NOAA or DoD missions.
  - NOS-T demonstration (White Paper).

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Publications

- Conference Papers

  AGU 2021: "StereoBit on the SpaceCube Mini" Carr, J., C. Wilson, D. Wu, M. French, M. Paolieri, H. Madani, M. Kelly

  AGU 2020: "StereoBit: Onboard Intelligence for Stereo Winds Constellation" Carr, J., C. Wilson, D. Wu, M. French, M. Kelly

  IGARSS 2020: An Innovative SpaceCube Application for Atmospheric Science Carr, J., C. Wilson, D. Wu, M. French, M. Kelly

- Submitted Journal Article (*Remote Sensing*)

  "Compact Midwave Imaging System: Results from an Airborne Demonstration" Kelly, M., J. Carr, D. Wu, A. Goldberg, I. Papusha, R. Meinhold

- Planned Journal Articles
  - IEEE StereoBit Development (Carr, 2xWilson, Wu, Madani)
  - VCE/Constellation (Paolieri, Wu, Carr)

List of Acronyms

1D	One-Dimensional
3D	Three-Dimensional
ADT	Application Development Testbed
AGU	American Geophysical Union
AIST	Advanced Information Systems Technology
APL	Applied Physics Lab
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
cFS	Core Flight System
CMIS	Compact Midwave Imaging System
CMS	Content Management System
Co-I	Co-Investigator
CPU	Central Processing Unit
CSV	Comma Separated Variable
CTI	Compact Thermal Imager
CYGNSS	Cyclone Global Navigation Satellite System
DEM	Digital Elevation Model
DS	Decadal Survey
ESTO	Earth Science Technology Office
FPGA	Field Programmable Gate Array
GEO	Geostationary Orbit
GOES-R	The Geostationary Operational Environmental Satellite R Series
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HARP	Hyper-Angular Rainbow Polarimeter
H&S	Hot and Spicy
HDL	Hardware Description Language
HLS	High-Level Synthesis
IEEE	Institute of Electrical and Electronics Engineering
IRAD	Internal Research & Development
ISI	Information Sciences Institute
ISS	International Space Station

List of Acronyms

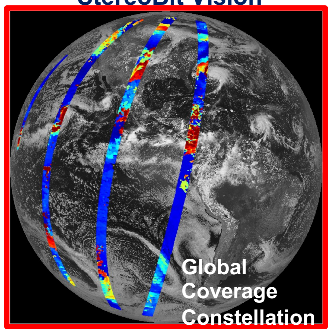
JHU	Johns Hopkins University
JPEG-LS	Joint Photographic Experts Group-Lossless Standard
JPL	Jet Propulsion Laboratory
LEO	Low-Earth Orbit
LiDAR	Light Detection and Ranging
MISR	Multi-Angle Imaging Spectro-Radiometer
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
PBL	Planetary Boundary Layer
PI	Principal Investigator
RRM3	Robotic Refueling Mission 3
SC	SpaceCube
SfM	Structure from Motion
SLSTR	The Sea and Land Surface Temperature Radiometer
SmallSats	Small Satellites
T2SL	Type-2 Super Lattice
TRL	Technology Readiness Level
USC	University of Southern California
VCE	Virtual Constellation Engine
WFIRST	Wide Field Infrared Survey Telescope

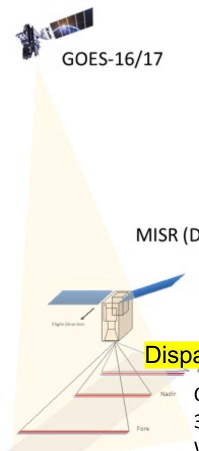
Backup Slides

3D Stereo Winds Method

Multi-Angle, Multi-Platform

StereoBit Vision

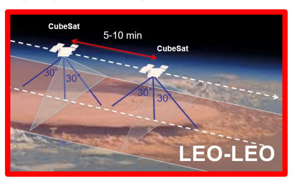




Disparities = Parallax + Motion

Carr, J.L., D.L. Wu, M.A. Kelly, and J. Gong, "MISR-GOES 3D Winds: Implications for Future LEO-GEO and LEO-LEO Winds," *Remote Sensing*, 2018, MISR Special Issue. https://www.mdpi.com/2072-4292/10/12/1885

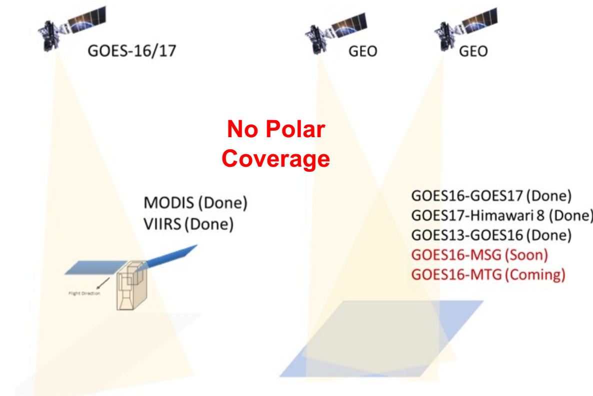
Multi-Platform: Resolves Height + In-Track Wind Ambiguity Existing with Single-Platform (e.g., MISR) Approach



LEO-LEO Enables Polar Coverage

LEO=Low-Earth Orbit GEO=Geostationary Orbit

Multi-Platform



Carr, J.L., D.L. Wu, R.E. Wolfe, H. Madani, G. Lin, B. Tan, "Joint 3D-Wind Retrievals with Stereoscopic Views from MODIS and GOES," *Remote Sensing*, 2019, Satellite Winds Special Issue. https://doi.org/10.3390/rs11182100

Carr, J.L.; Wu, D.L.; Daniels, J.; Friberg, M.D.; Bresky, W.; Madani, H. "GEO-GEO Stereo-Tracking of Atmospheric Motion Vectors (AMVs) from the Geostationary Ring," *Remote Sensing*, 2020. https://doi.org/10.3390/rs12223779

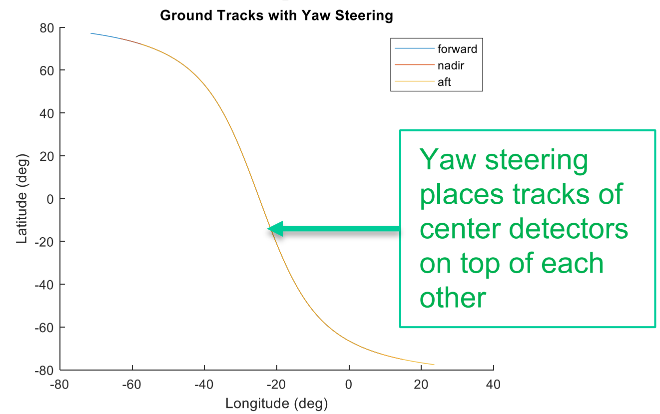
Technical Readiness Level (TRL)

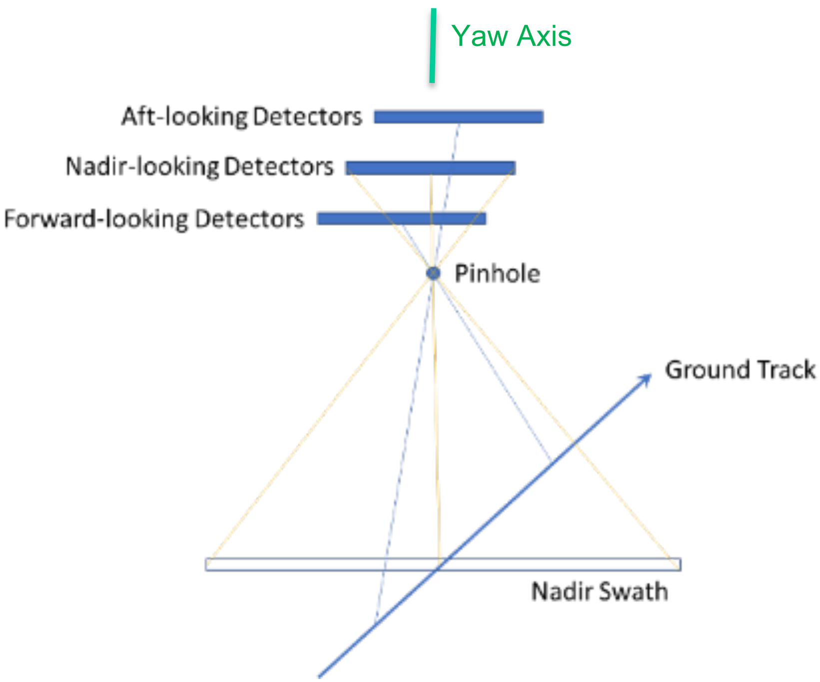
Subsystem / Component	Entry TRL	Exit TRL	Relevant Justification
StereoBit SfM component hosted on CPU/FPGA hybrid spacecraft processor **TRL 5.** Step (1) done in lab during IR&D, Step (2) synthesized pipeline code run on dev board and verified end-to-end against pipeline and Level-2 science code. TRL 6 by Final Demo 01/22 with cFS application on SC 3.0 hardware.	4	6	**Entry:** SfM algorithm implemented and functionally validated during IRAD project on an FPGA development board in laboratory environment. **Steps to TRL 5:** (1) Flight demonstration of IRAD SfM algorithm on SC 2.0 hardware on ISS*; (2) Implementation of full SfM and compression algorithms meeting predicted performance on SC 3.0 development board as needed to support advanced MWIR cameras (e.g., CMIS). **Exit:** Integrated prototype flight code running over cFS on SC 3.0 hardware in Application Development Testbed and demonstrated with flight-realistic inputs.
StereoBit 3D Winds retrieval end-to-end disaggregated science data processing subsystem **TRL 6.** Complete by Final Demo 01/22.	5	6	**Entry:** (1) 3D-Wind retrieval algorithm implemented in Matlab and validated with MISR+GOES datasets; (2) cloud- enabled Virtual Constellation Engine from AIST-16. **Exit:** Integration of end-to-end science data processing in the Application Development Testbed to demonstrate operations of flight (including SfM algorithms above) and ground subsystems and integrated operations between different platforms.

*CTI cryocooler failure

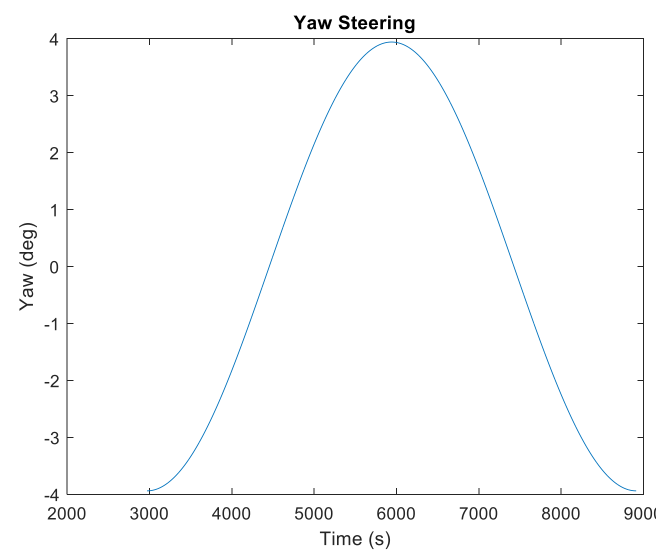
Yaw Steering

- Postulate Yaw Steering to maximize overlap of Forward-Nadir-Aft detector swaths in presence of Earth rotation

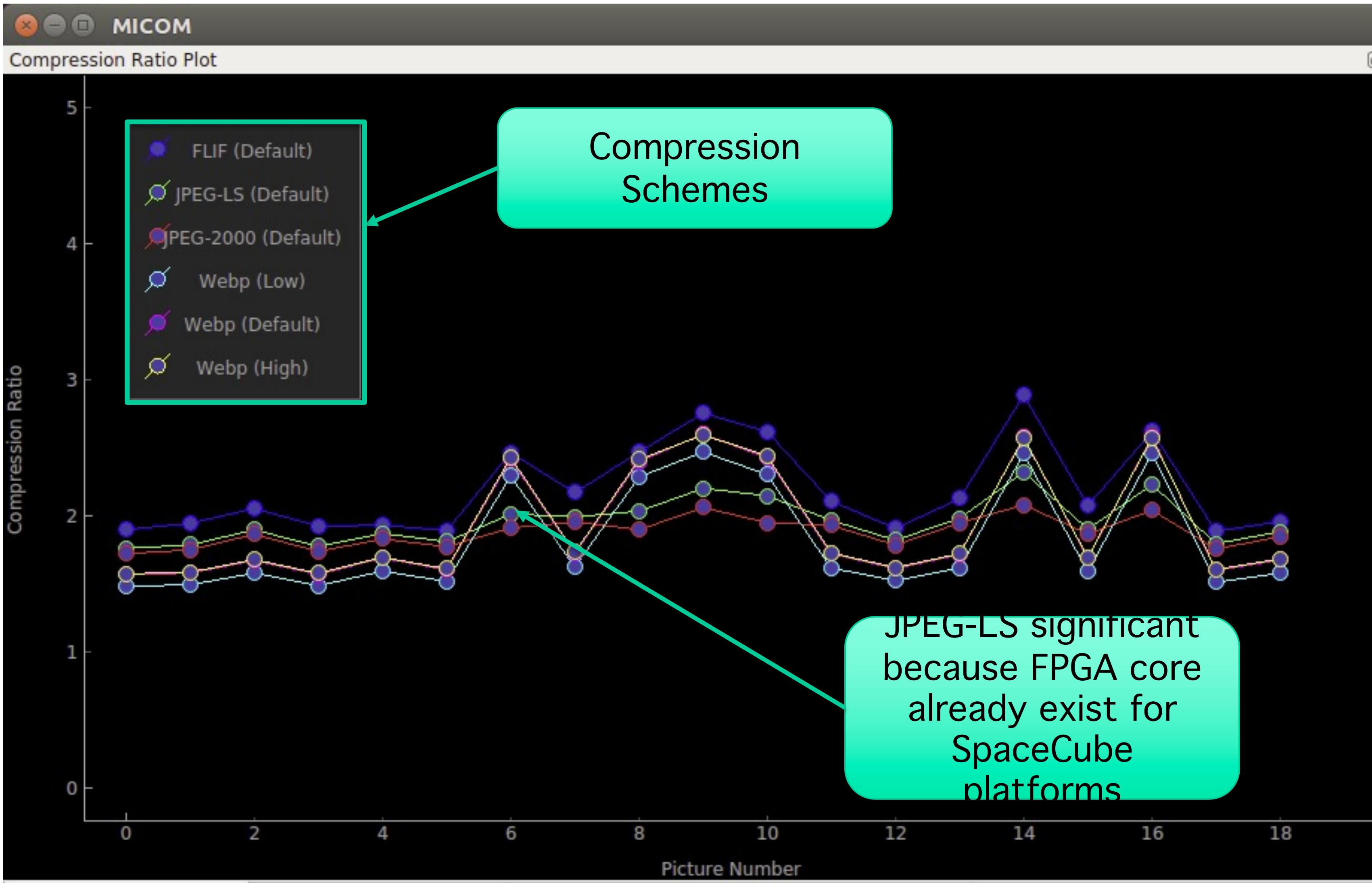




Ground-Track & Orbital Velocity not Parallel due to Earth Rotation

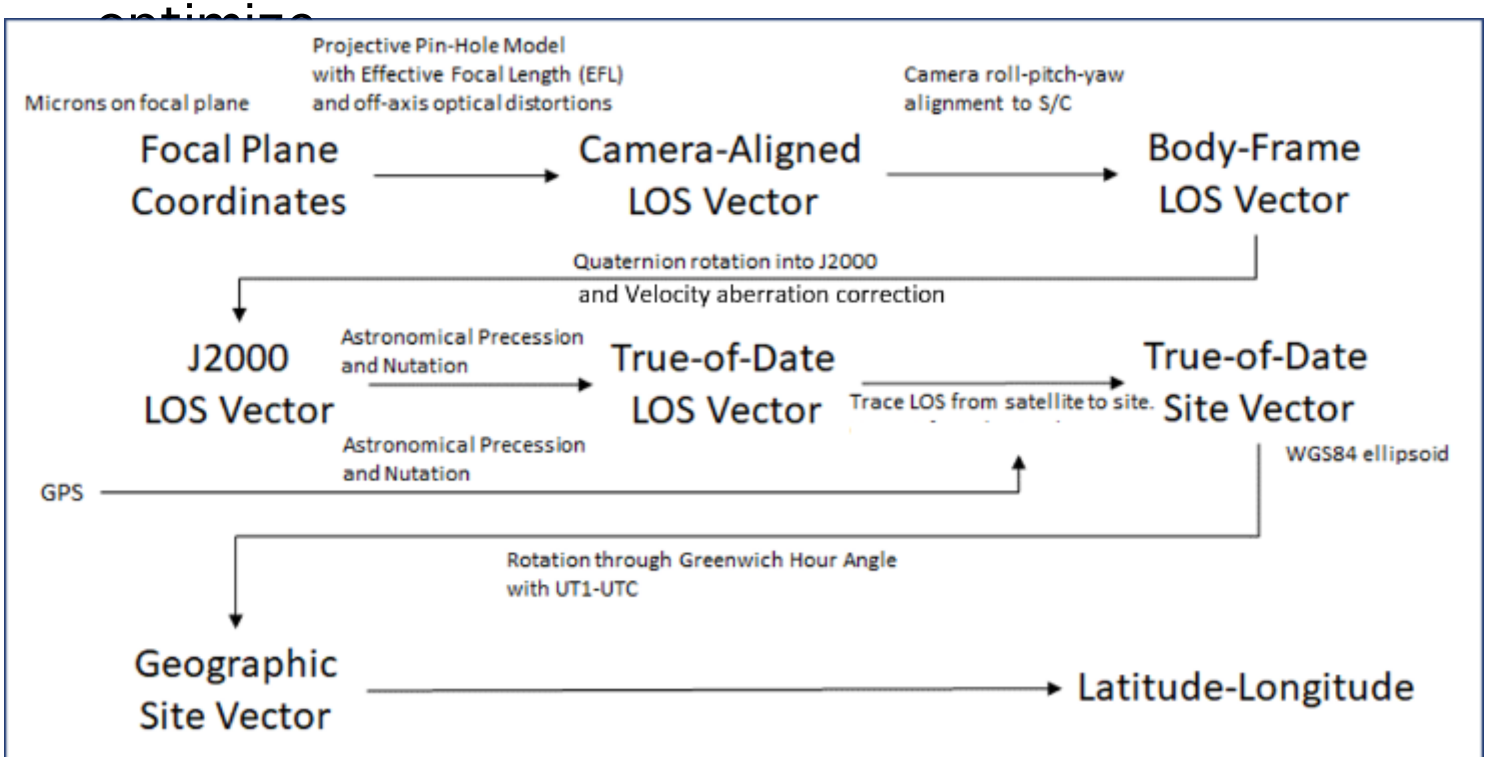


Compression Ratio Plot

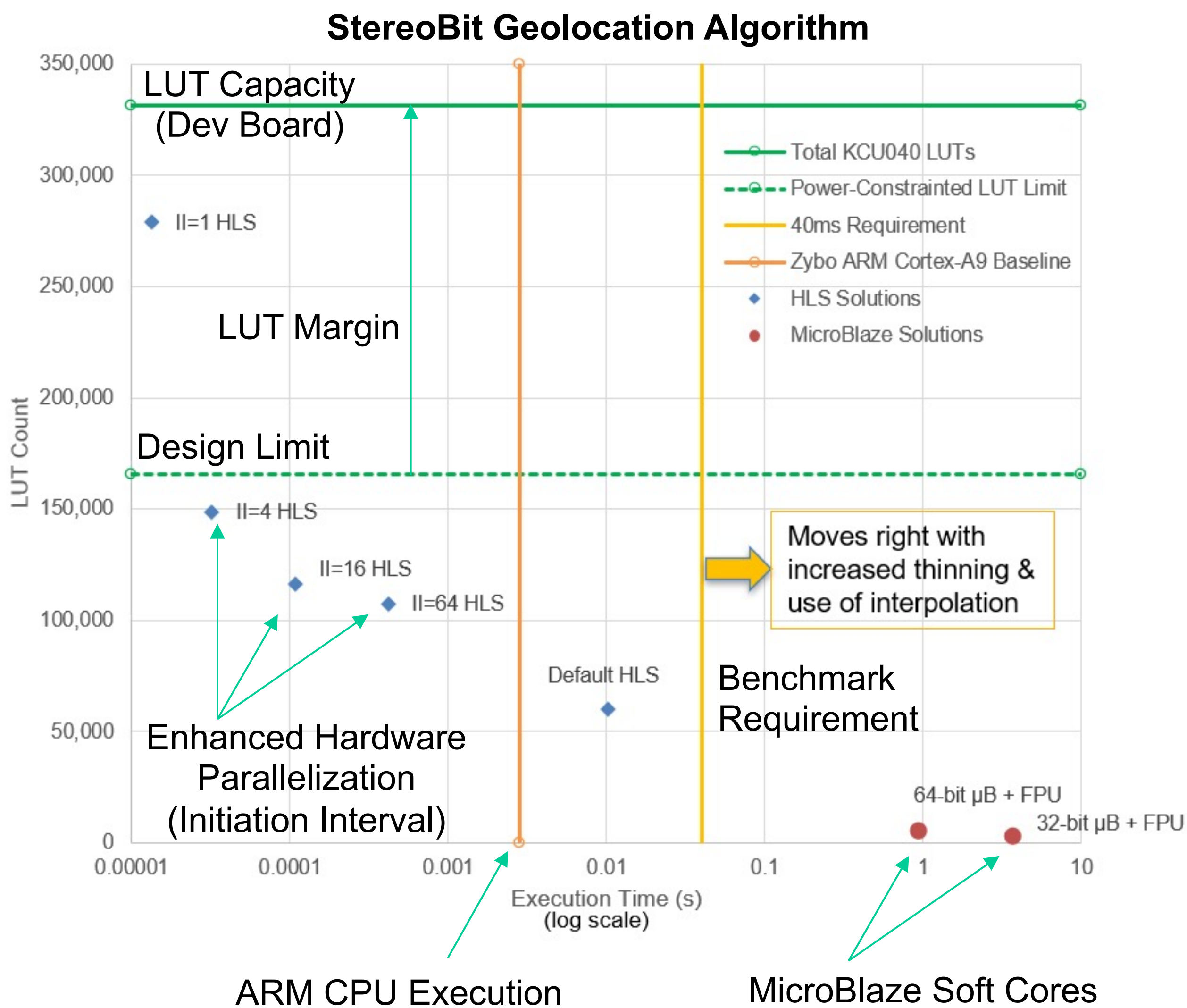


Onboard Geolocation

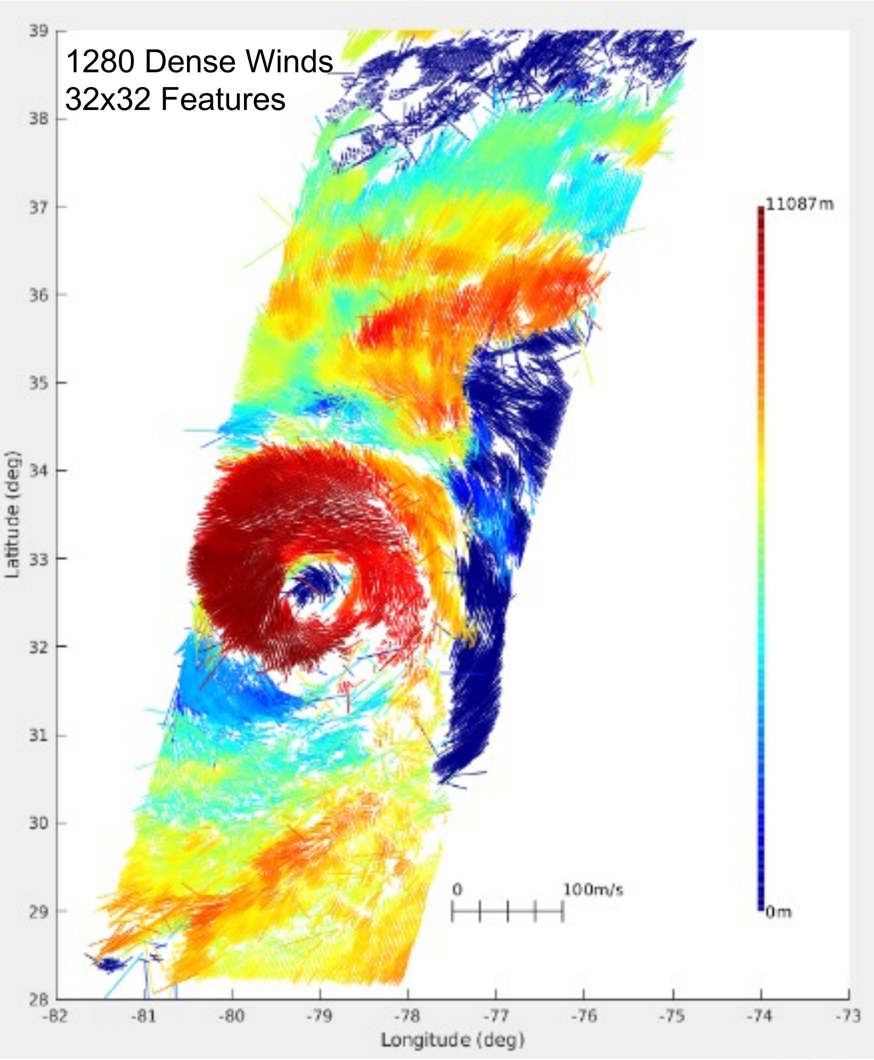
- Uses GPS, quaternions, and optical calibration parameters to calculate (lat,lon) coordinates for pixels
- Based on GOES-R GLM algorithm
- C-code tested and delivered to GSFC colleagues for synthesis and testing on HW. Iterations possible to optimize



Acceleration of Geolocation

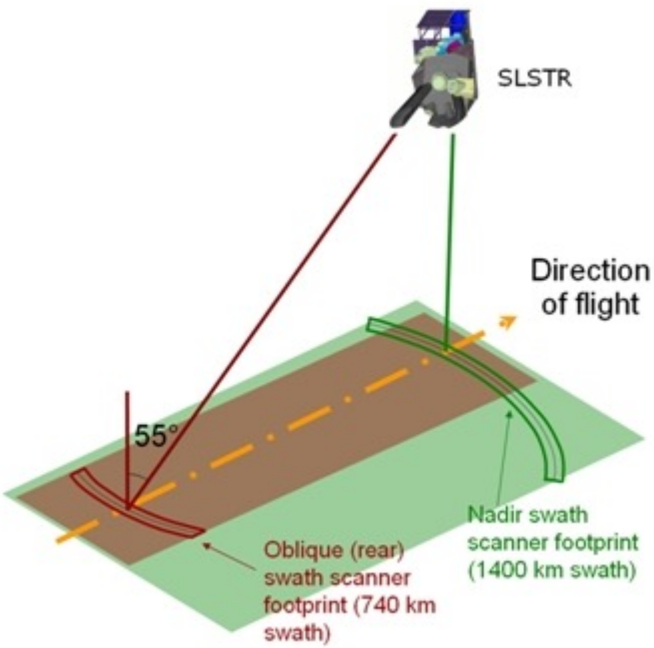


StereoBit High Density 3D Winds



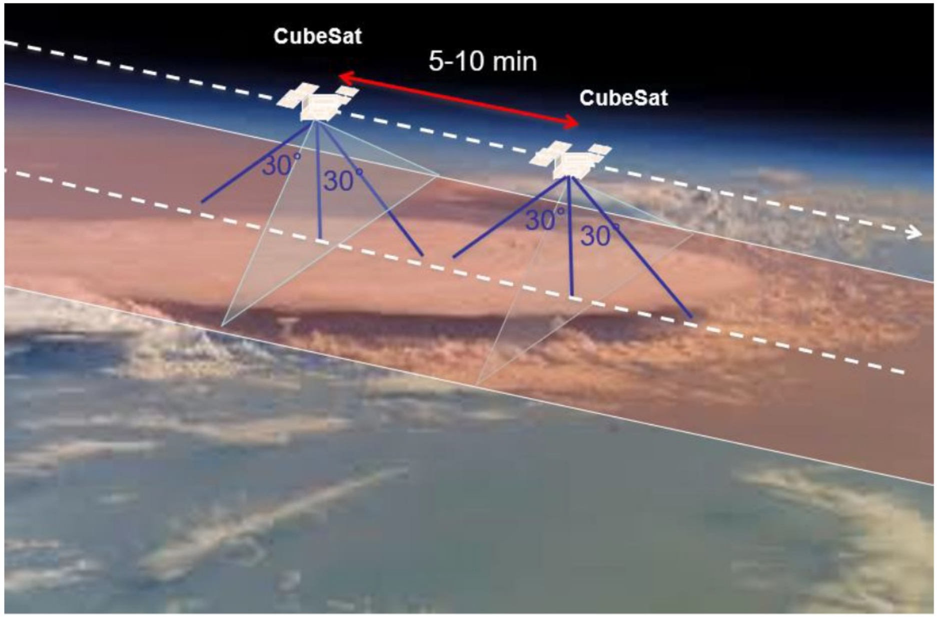
Leader-Follower Demonstration

- Leader-Follower StereoBit Implementation Proven with Sentinel-3A and -3B SLSTR Proxy Data



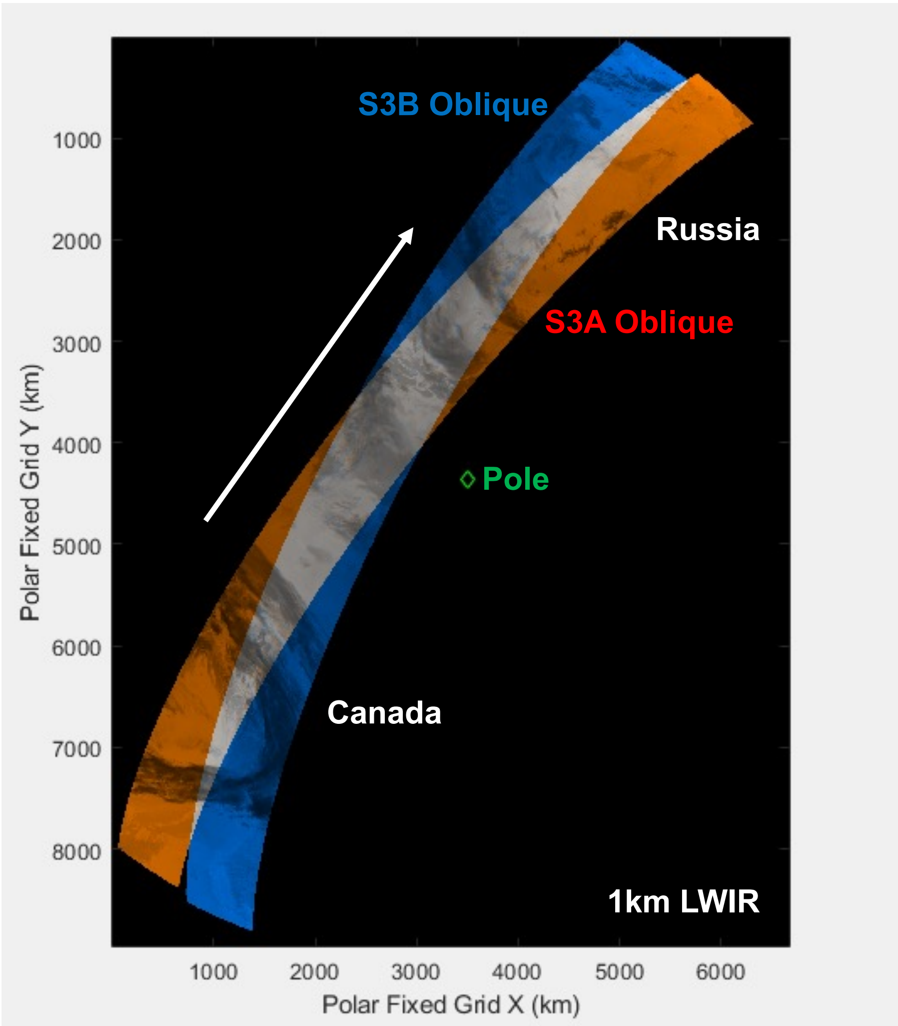
2 x 2 Looks

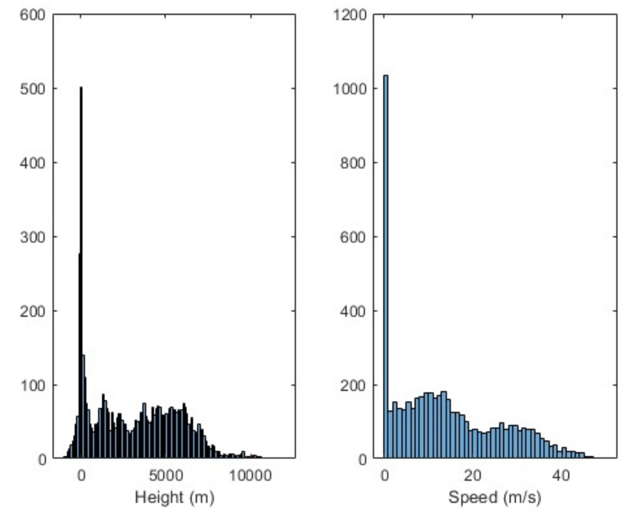
StereoBit Leader-Follower

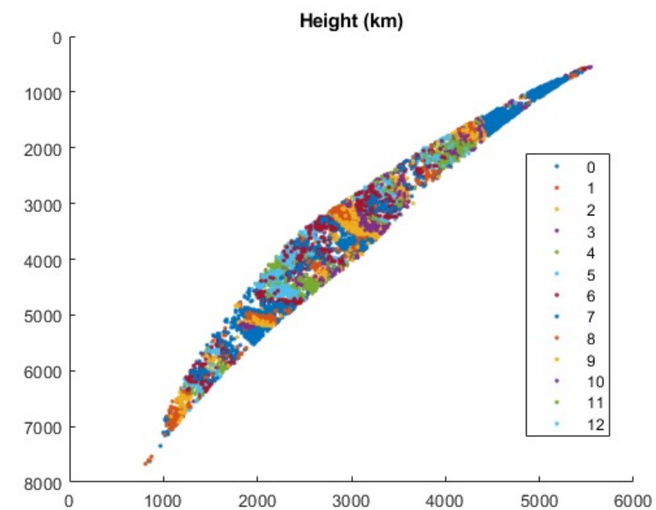


2 x 3 Looks

Leader-Follower SLSTR Demo



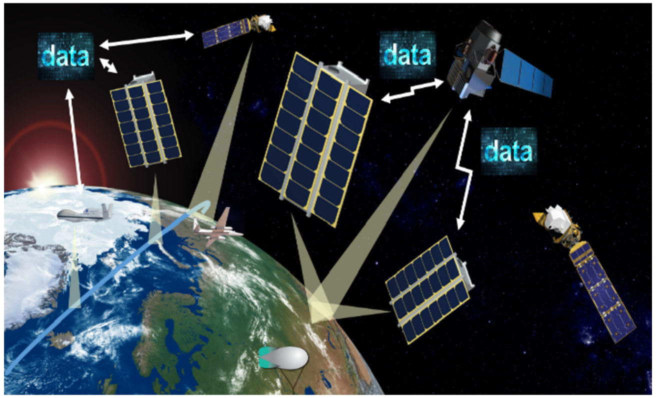




Virtual Constellation Engine: Motivation

Autonomous constellations and sensor webs

- Onboard intelligence
- Coordination



New observing strategies

- Respond to dynamic events
- Collect data from multiple points/instruments

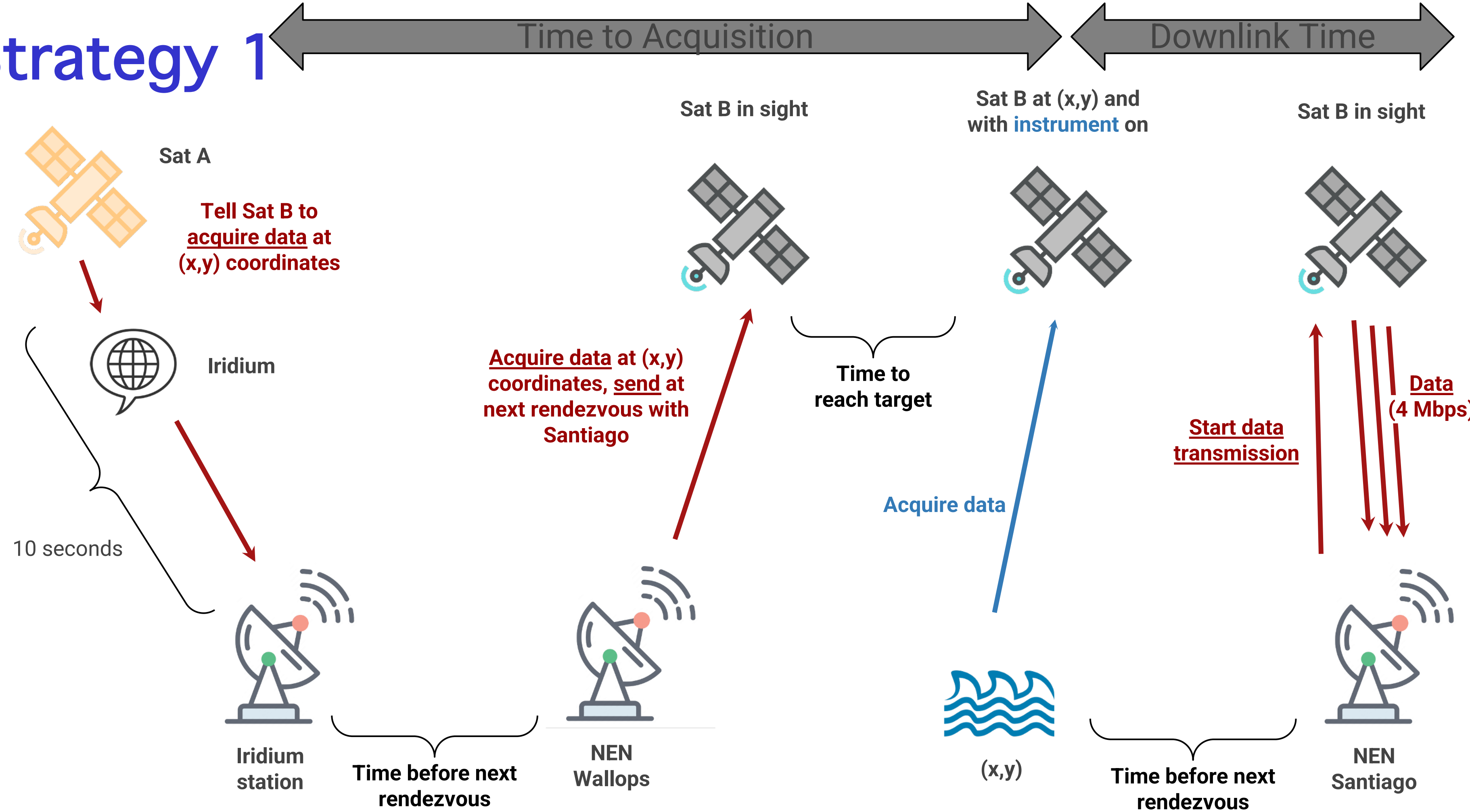
Onboard computing and communication

- Critical for these capabilities
- Difficult to validate mission concepts, HW and SW for distributed remote sensing systems

ESTO Earth Science Technology Office

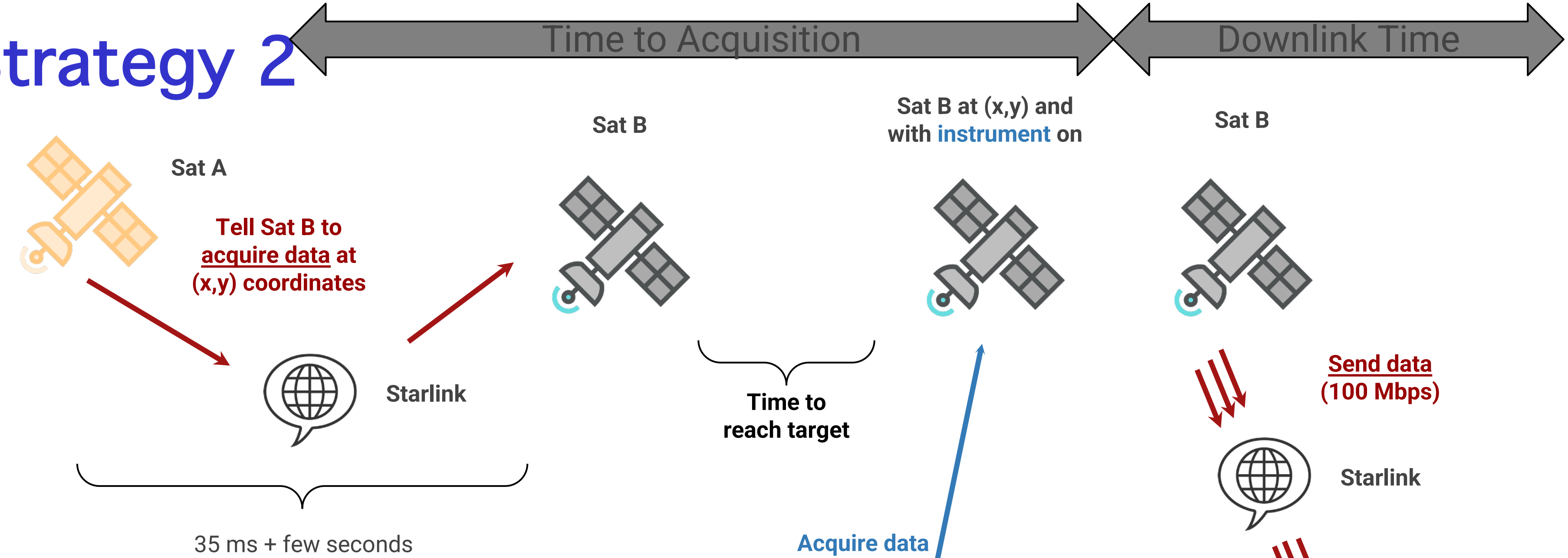
Ground Network

Strategy 1



Global Network

Strategy 2



Global Starlink network

- Satellite ↔ satellite and satellite ↔ ground communication
- Avoids the rendezvous to receive commands from ground
- Avoids the rendezvous for downlink of acquired data
- Avoids the use of NEN ground stations
- Major latency source: time to reach target

(Application payload will be hosted on a Starlink satellite.)

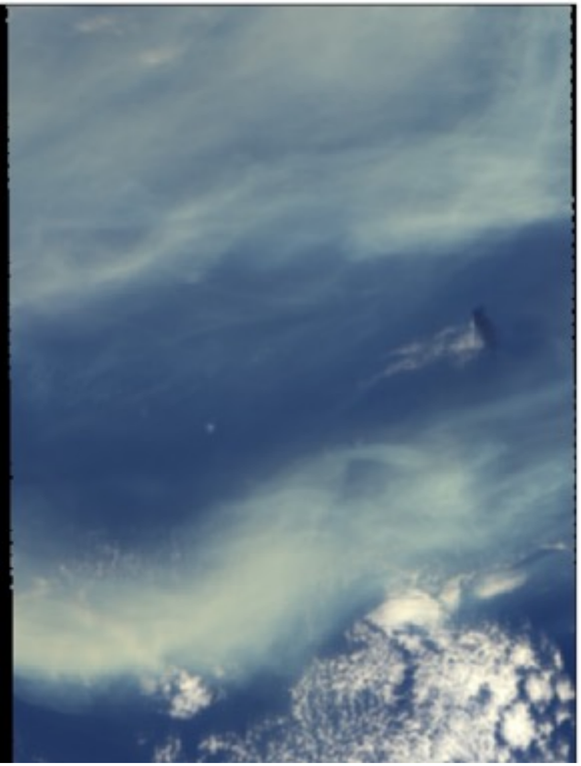
Lossy Compression Testing (Aerosols)

MISR JPEG-2000 Compressed Input vs Retrieved Aerosol Output

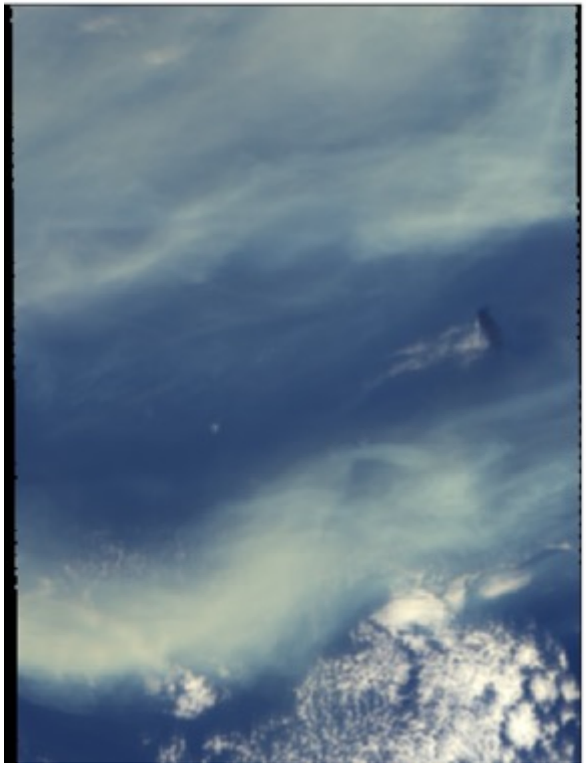
MISR Orbit 100531, Blocks 66-69
Camp Fire Offshore Plumes

James Limbacher, GSFC

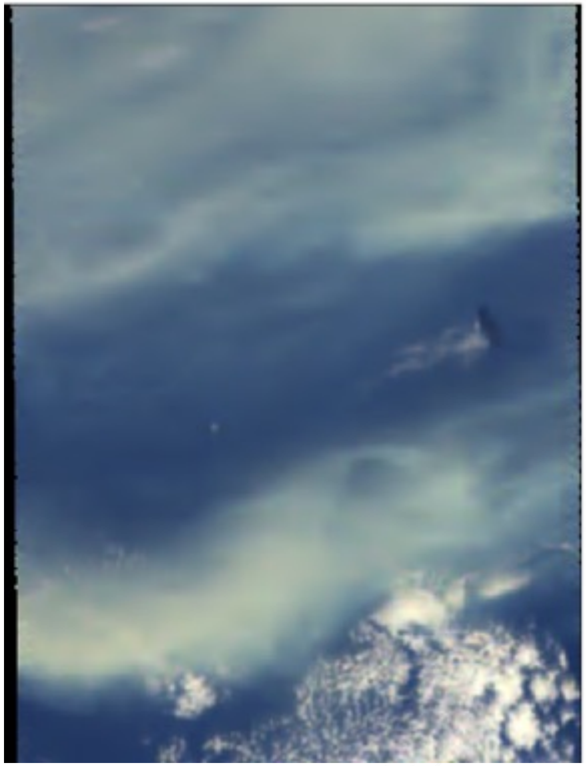
1x, Df RGB
14.1 MB

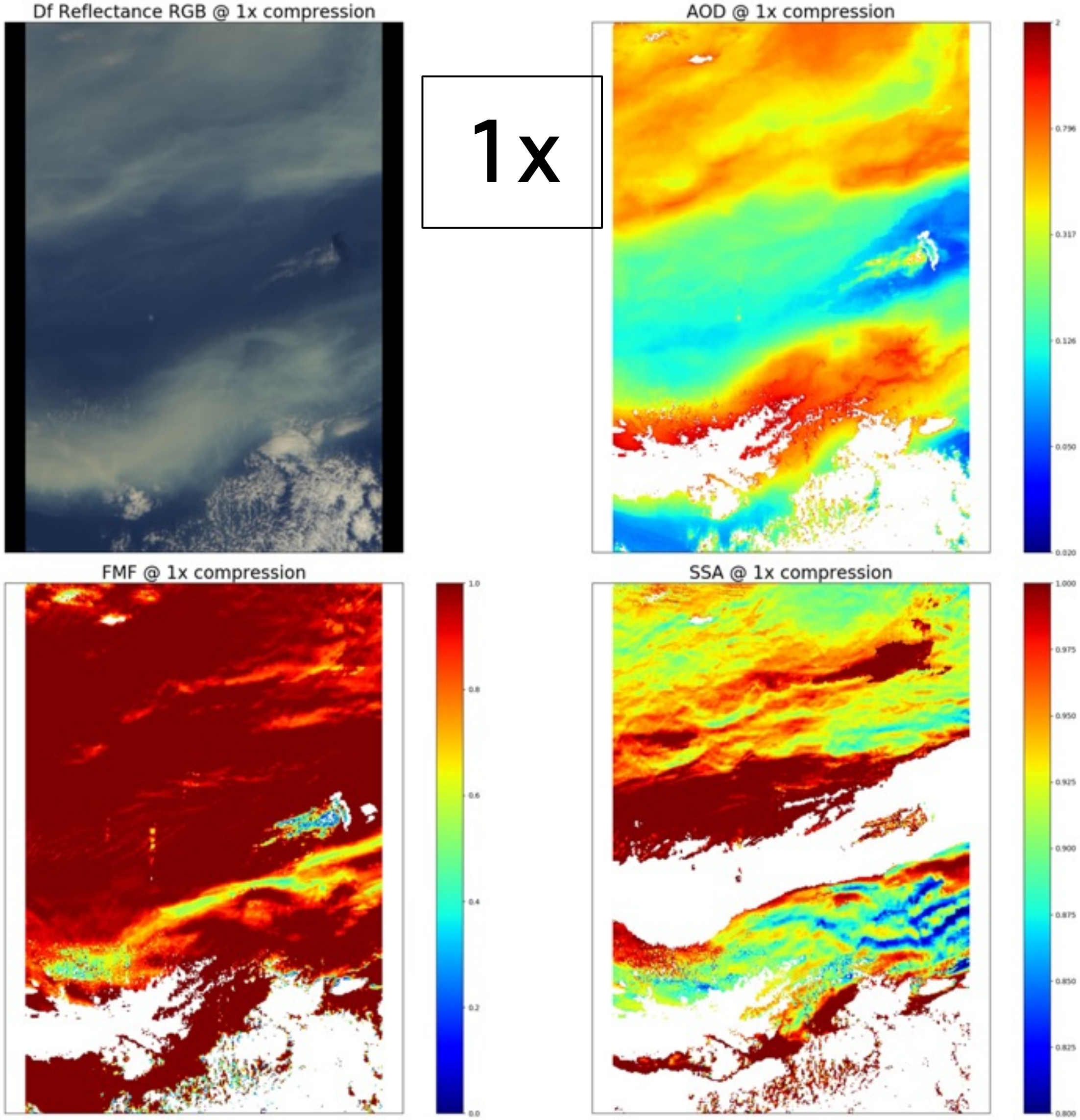


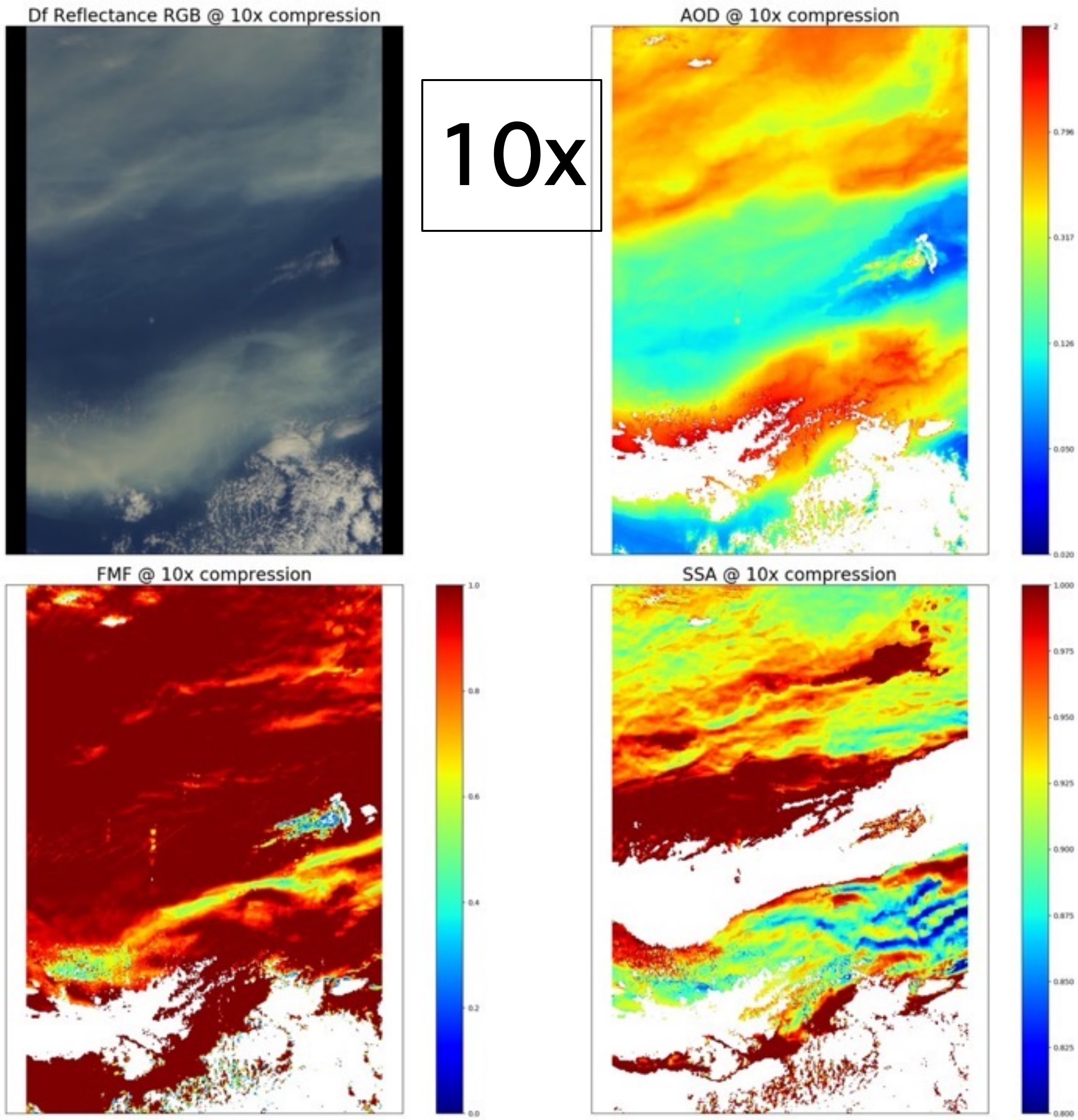
10x, Df RGB
1.3 MB

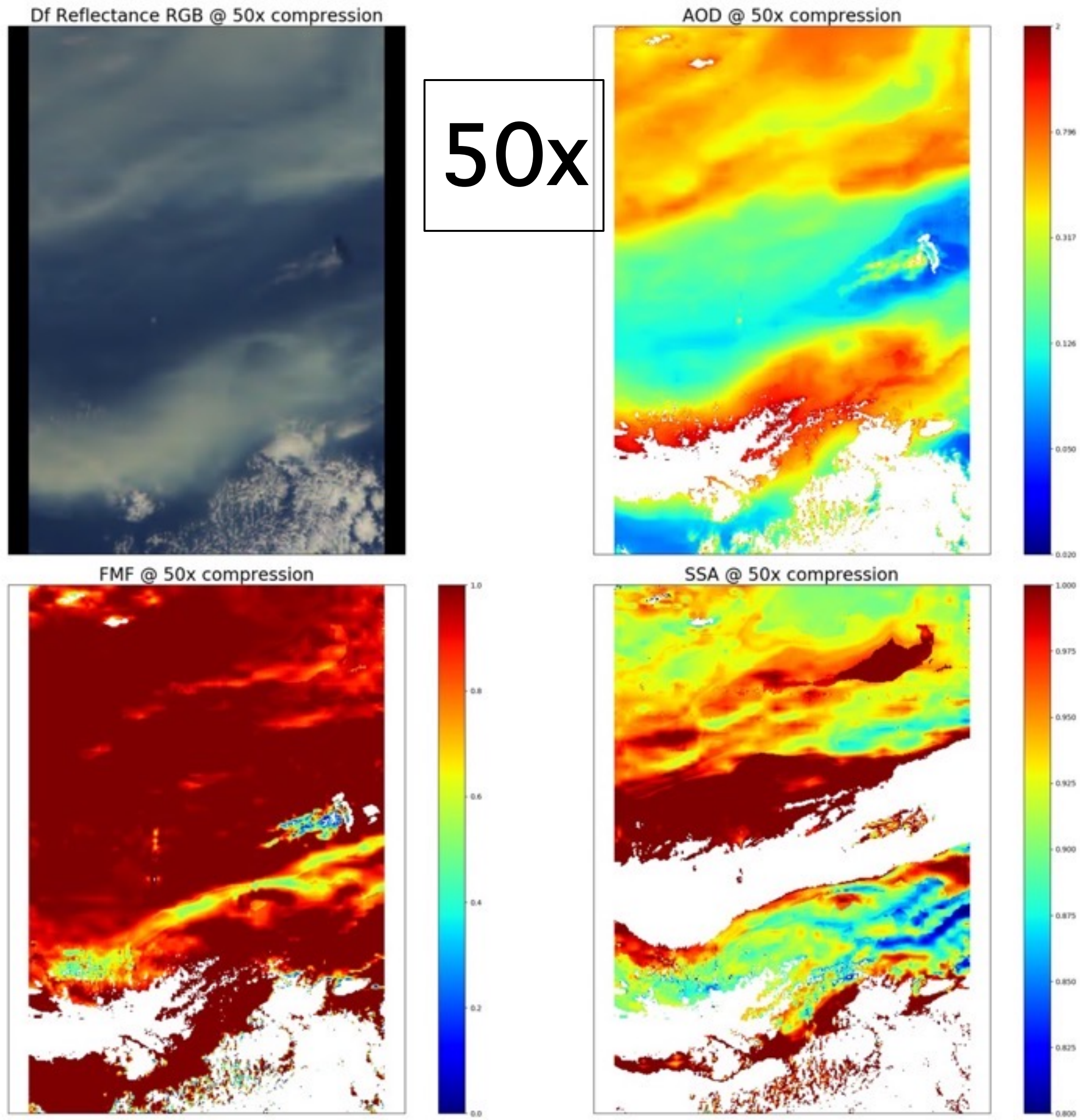


50x, Df RGB
0.28 MB




Df Reflectance RGB @ 1x compression
1x
AOD @ 1x compression
2
0.796
0.317
0.126
0.050
0.020
FMF @ 1x compression
1.0
0.8
0.6
0.4
0.2
0.0
SSA @ 1x compression
1.000
0.975
0.950
0.925
0.900
0.875
0.850
0.825
0.800

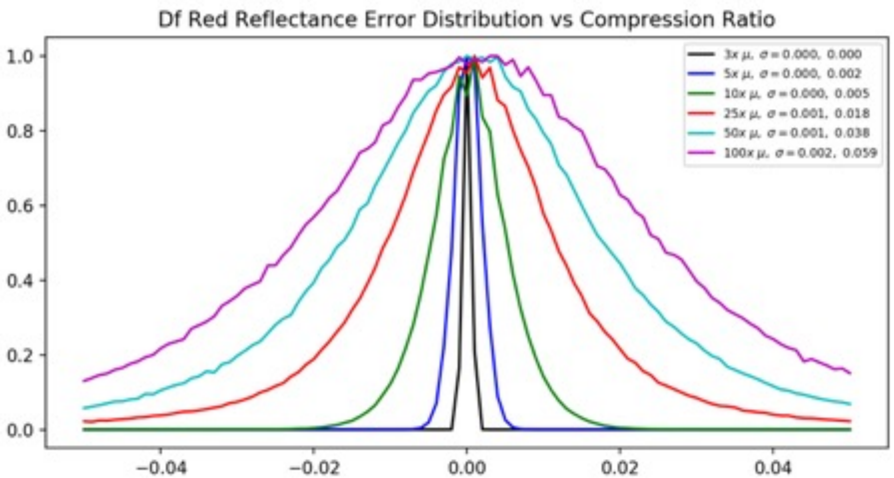

Df Reflectance RGB @ 10x compression
10x
AOD @ 10x compression
FMF @ 10x compression
SSA @ 10x compression

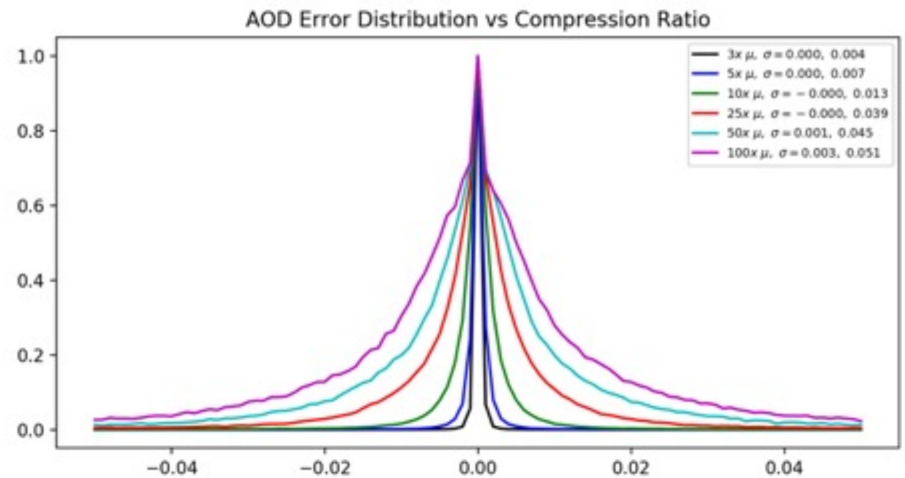

Df Reflectance RGB @ 50x compression
50x
AOD @ 50x compression
2
0.796
0.317
0.126
0.050
0.020
FMF @ 50x compression
1.0
0.8
0.6
0.4
0.2
0.0
SSA @ 50x compression
1.000
0.975
0.950
0.925
0.900
0.875
0.850
0.825
0.800

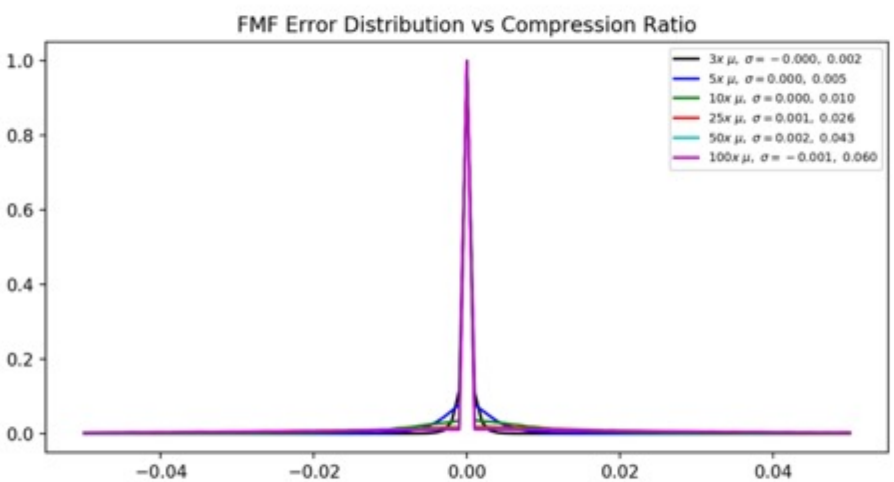
Error Histograms

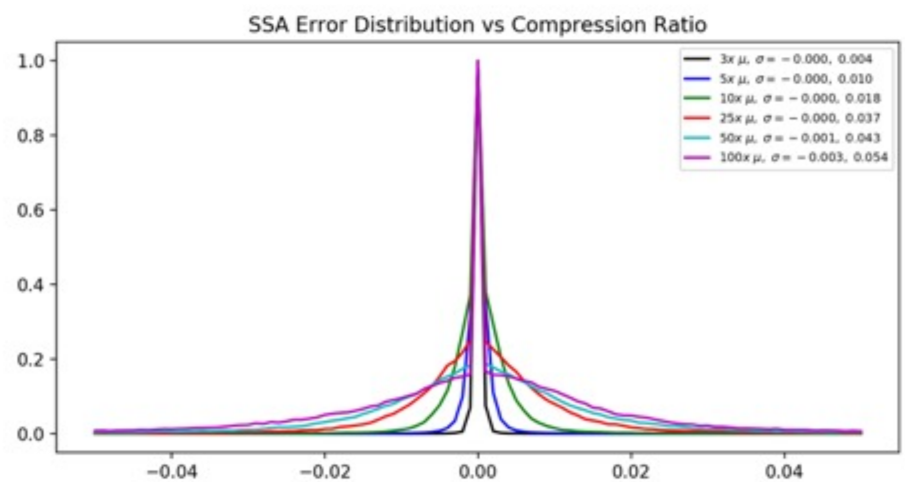
MISR Orbit 100531, Blocks 66-69

Camp Fire Offshore Plumes









SPCTOR: Sensing-Policy Controller and OptimizeR

AIST-18-0077 Annual Technical Review
Jan. 7th 2022

Mahta Moghaddam[1], PI
Dara Entekhabi[2], Co-I
Ruzbeh Akbar[2]
Agnelo R. Silva[3], Consultant
Sam Prager[1]

[1]University of Southern California, Los Angeles, CA, USA
[2]MIT, Cambridge, MA, USA
[3] Consultant (also with METER Group Inc. Pullman, WA, USA)

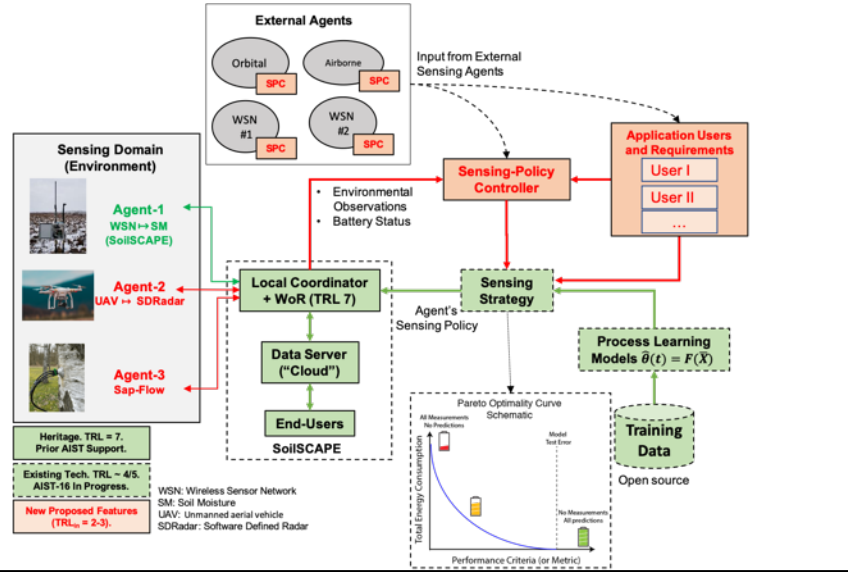
SPCTOR: Sensing-Policy ConTroller and OptimizeR

PI: Mahta Moghaddam, USC

Objective

Develop a framework to coordinate and optimize sensing strategies, in particular for soil moisture profiles, across multiple Agents by means of a new machine-learning-based entity. Specific objectives are:

1. Develop a Sensing-Policy Controller (SPC) for multi-Agent observation strategy coordination and optimization. (NOS elements b and c).
2. Develop and demonstrate integrated operations between in situ wireless sensor networks and unmanned aerial vehicle (UAV) based software defined radars (SDRadars) for optimized spatiotemporal root-zone soil moisture observations (NOS element a)



Approach

1. Define in-situ networks and UAV-bases sensors as "Agents" providing complementary spatial and temporal samples of science quantity under observation; targeted quantity is surface-to-root-zone profiles of soil moisture
2. Build upon existing SoilSCAPE (TRL ~ 7) heritage and expand Local Coordinator (LC) function to interoperate with UAVs
3. Integrate SDRadar as a payload into UAV
4. Generate "Pareto Curves" – energy vs performance – for different Agents based on Application Users
5. Generate and optimize "Contract Curve" between Agents
6. Using new observations and updated application requirements, optimize/update/coordinate observation strategies between Agents, including optimal UAV path planning

Co-Is/Partners: Dara Entekhabi (MIT), Agnelo Silva, (METER)
Ruzbeh Akbar (Research Scientist, MIT)

Key Milestones (includes COVID impact)**

• Define target user application scenarios of SPC	01/20
• Develop Sensing Policy pareto-optimal curves for WSN and UAV; develop trade-off framework using ML approaches	06/20
• UAV-SDRadar and data server integration: software demo	12/20**
• Assemble UAV-SDRadar and integrate LC-WoR with UAV	03/21**
• Lab demonstration of WSN-LC and UAV communication	**07/21****
• Initial WSN-UAV interoperation demo in-field (Walnut Gulch)	**08/21****
• 2nd controlled UAV-WSN demonstration (USC or WG)	**02/22****
• Final WSN-UAV interoperation demo in-field (Tonzi or WG)	04/22**

** Flexible Milestones related to field work and demos

SPC TRL$_{in}$ = 2   WSN-UAV TRL$_{in}$ = 4

Presentation Contents

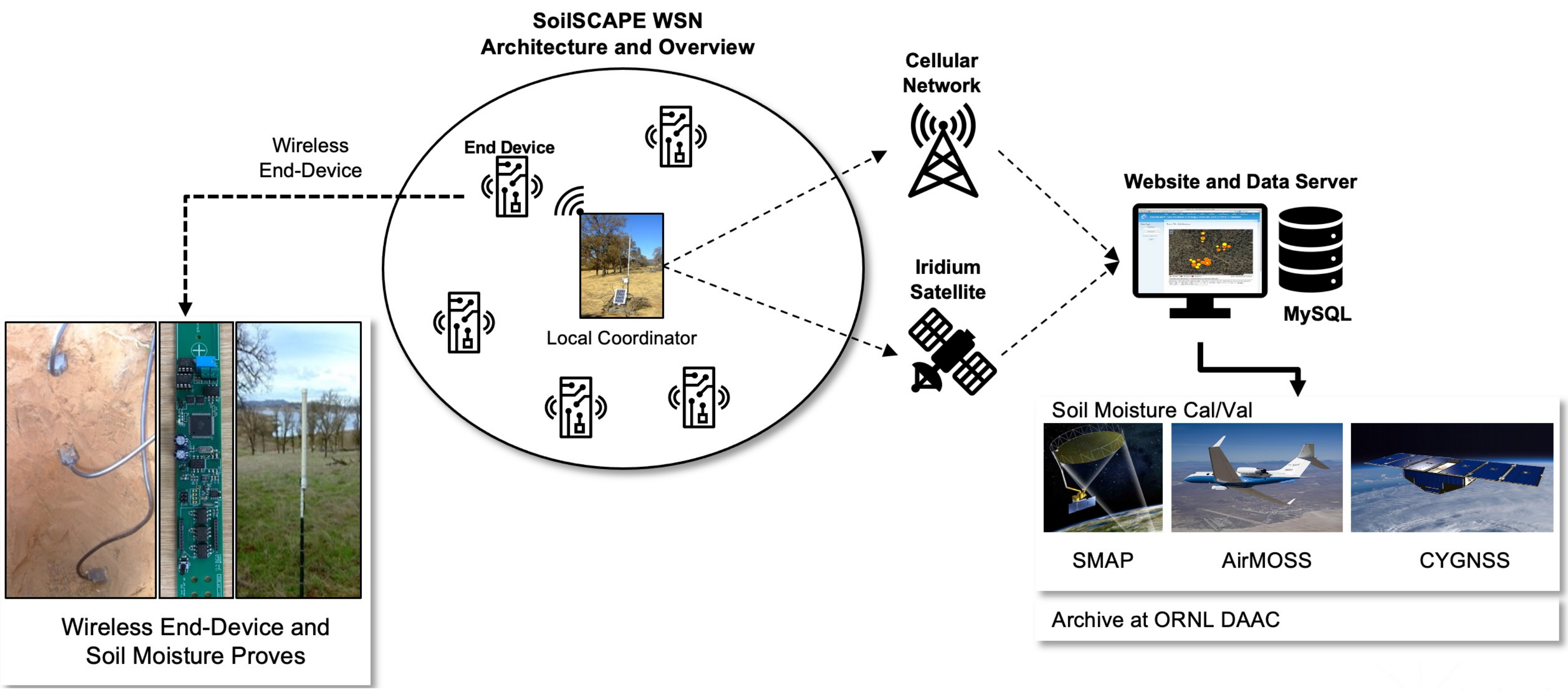
- Background and Objectives
- Technical and Science Advancements
- Summary of Accomplishments and Future Plans
- Actual or Potential Infusions and Collaborations
- Publications - List of Acronyms

Background and Objectives

Existing technology heritage in Wireless Sensor Networks (WSN)

- **SoilSCAPE**: Soil Moisture Sensing Controller and Optimal Estimator (TRL 7)
- Clusters of medium-scale (< 500 [m]) *in situ* (WSN) to measure near real-time surface-to-root zone soil moisture (top 5 [cm] – 100 [cm])
- SoilSCAPE primary objectives:
  - Advancement in low-power wireless sensing technologies.
  - *Ground truth soil moisture for NASA Earth Science missions*

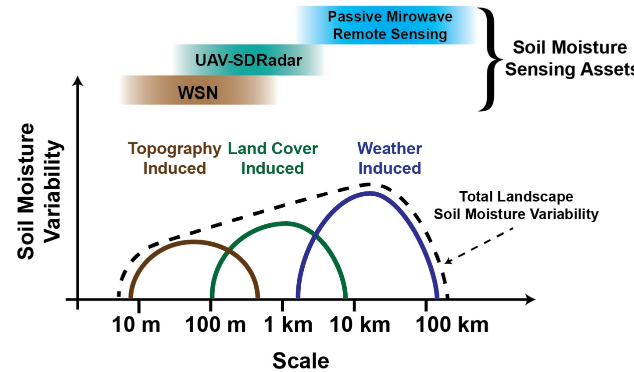
NASA CYGNSS Mission has commissioned a series of SoilSCAPE sites for its soil moisture cal/val efforts



Background and Objectives

SPCTOR = SoilSCAPE + UAVs

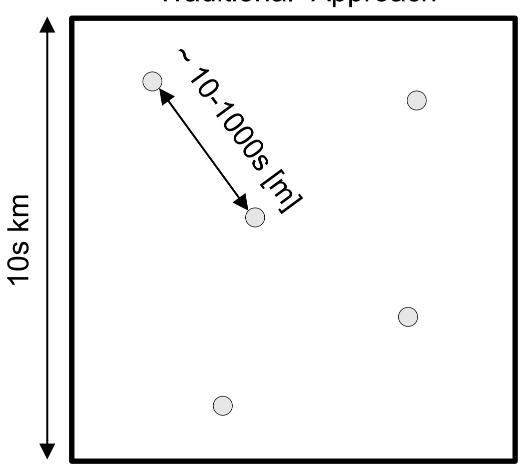
1. Soil moisture is highly variable across the land-scape.
2. Land-scape heterogeneity is “averaged” within field of view of Earth observation soil moisture satellites.
3. Observation technologies for in situ soil moisture monitoring needed for satellite “cal/val.”
4. Distributed wireless sensor networks (WSNs) within FOV will increase spatial sampling and representativeness.



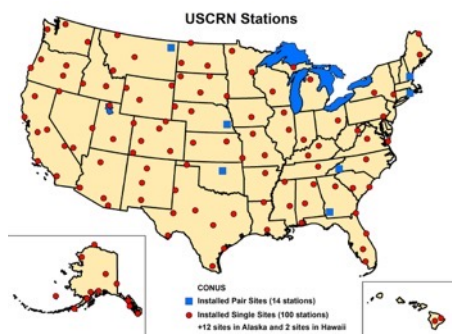
WSN are:

1. Static and fixed in space.
2. Limited capabilities in wide-spread network coverage and deployment costs
3. **Technology solution: Utilize mobile assets such as UAVs with radar payloads**

“Traditional” Approach

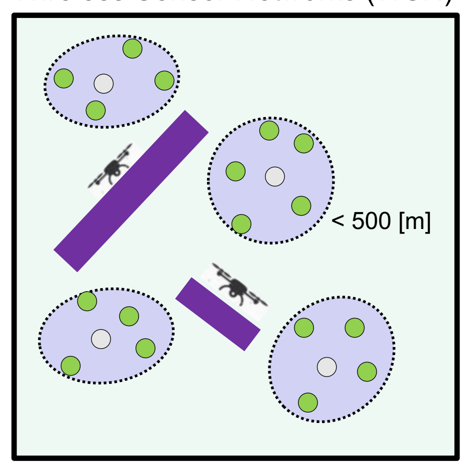


Single (Point) Soil Moisture station



https://www.ncdc.noaa.gov/crn/

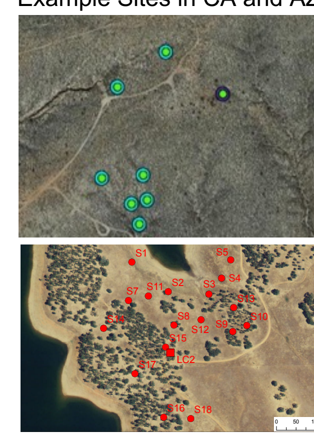
Wireless Sensor Networks (WSN)



WSN Cluster (< 30 Nodes)

UAV Flight Path

Example Sites in CA and AZ



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Technical and Science Advancements
Hardware Integration (1)

SCPTOR includes *two independent and discrete sensing systems*:

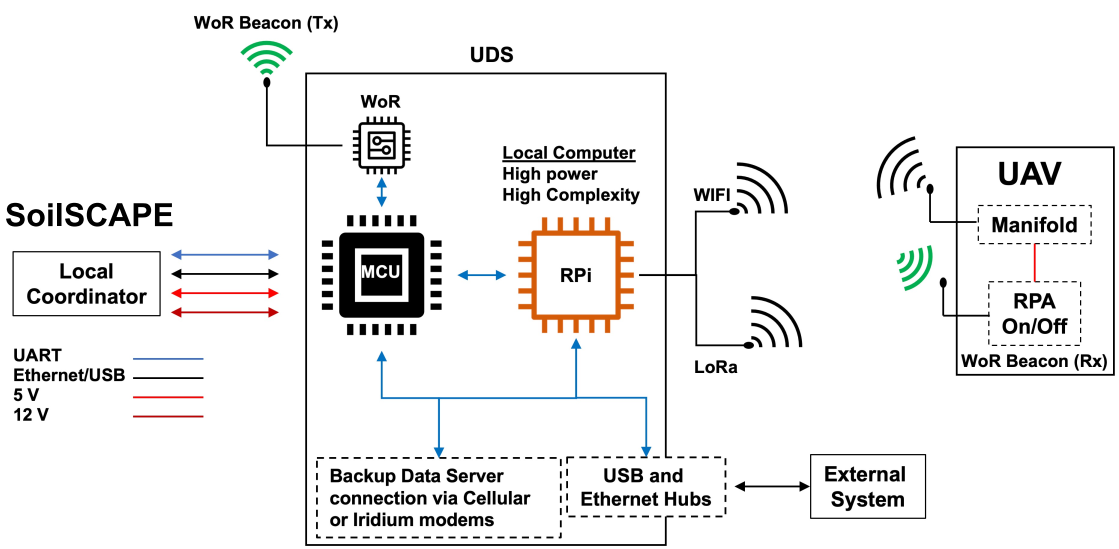
- SoilSCAPE WSN (TRL 7)
- UAV with SDRadar payload (TRL 4)

Hardware:

- Custom WSN-UAV interface board (UAV Data Server (UDS)-board)
- Custom remote UAV power switch
- UDS enables two-way Ethernet, WIFI, and UART connectivity between UAV and WSN

Software:

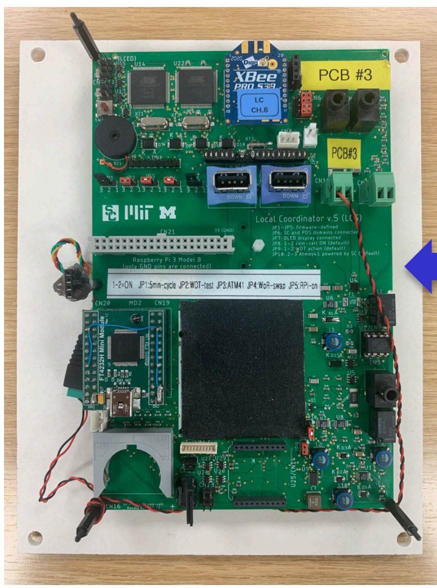
- XML-like UAV mission file generation: GPS waypoints and SDRadar settings
- Gaussian Process Regression and Mixed Integer Programing-based UAV path planning



Technical and Science Advancements
Hardware Integration (2)

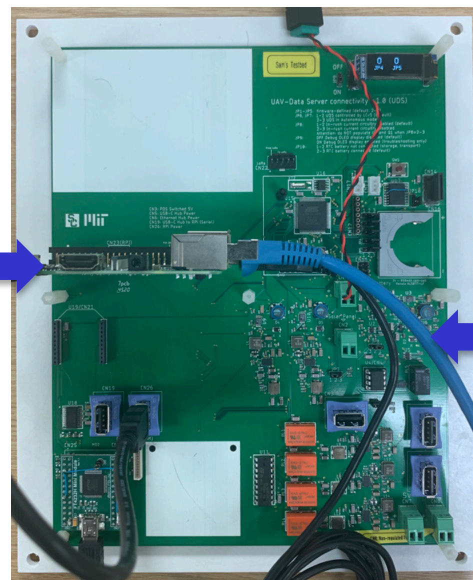
- Python-based software on LC, UDS, and UAV manifold for data and message passing.
- UDS can be extended to other platforms
  - WIFI and LoRa available
  - Additional custom software maybe required

SoilSCAPE Local Coordinator

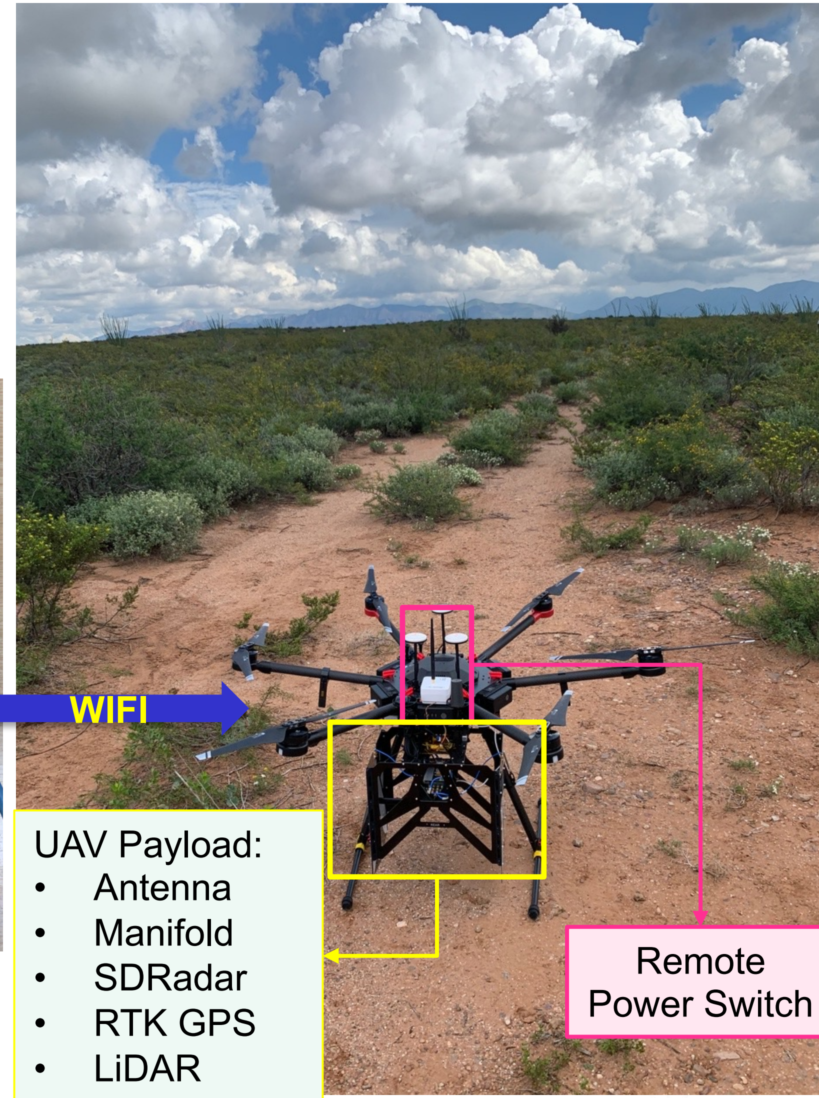


Ethernet

UAV-WSN Interface Board

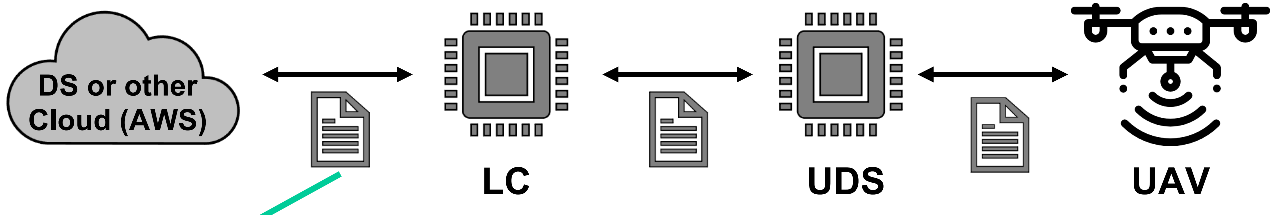


WIFI



Technical and Science Advancements
Mission File Generation

Mission generate at SoilSCAPE data server (DS)

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<?xml version="1.0" encoding="utf-8"?>
<root>
    <tid>1</tid>
    <uav name="uavA" location="Los Angeles, CA">
        <flightplan name="flight1" date="11032020" time="113200">
            <waypoint>"34.162022,-118.258758,10"</waypoint>
            <waypoint>"34.162522,-118.258658,10"</waypoint>
            <waypoint>"34.163022,-118.258558,10"</waypoint>
        </flightplan>
    </uav>
    <sdradar name="A" location="Los Angeles, CA">
        <freqs>"1e9:40e6:2e9"</freqs>
        <rxgain>40</rxgain>
        <txgain>30</txgain>
        <waveuse>tukey50.bin</waveuse>
        <sweeps>20</sweeps>
        <sri>1</sri>
        <num>10</num>
        <avg></avg>
        <secfuture>.001</secfuture>
        <pri>3e-4</pri>
        <fdxcal>0</fdxcal>
        <fastfreqhop>1</fastfreqhop>
        <cals>0</cals>
        <numcal>10</numcal>
        <file>spctor_uavsdradar_demo/out.dat</file>
        <notransfer></notransfer>
    </sdradar>
</root>
```


Flight path GPS way-points.
Manually set, or from Path Planning Algorithm
NOS-like nodes can also generate flight path

SDRadar parameter set (e.g., sweep, frequency, BW)
Affects flight duration, velocity, data volume and measured soil moisture

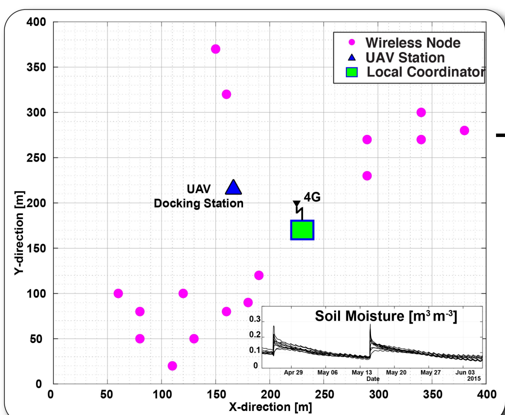
Soil Moisture Informed UAV Path Planning

How do we determine the UAV flight path?

1. In situ WSN soil moisture input to *Gaussian Process Regression* model to generate "uncertainty map", u_{ij} (Analogous to C-space in robotics)
2. Mixed Integer Programming (MIP) to maximize UAV round-trip flight over soil moisture uncertainty map*

$$\max \sum_{i,j}^{N} u_{ij} \cdot x_{ij} \; ; \quad x_{ij} \in \{0, 1\} + \textbf{UAV Flight Constraints} + \textbf{SDRadar Constraints}$$

- Offline MIP solver yields GPS ways points for UAV-SDRadar (GUROBI OPTIMIZATION)
- UAV range constrained by payload mass, and velocity constrained by SDRadar settings



(a)

UAV Path Planning

Step 1: Soil Moisture Upscaling via Gaussian Process Regression

Inputs:
- WSN in situ sensors
- UAV soil moisture (when available)

Outputs:
- Gridded soil moisture estimates
- Gridded soil moisture uncertainty

(b)

Step 2: MIP Optimization and Path Planning

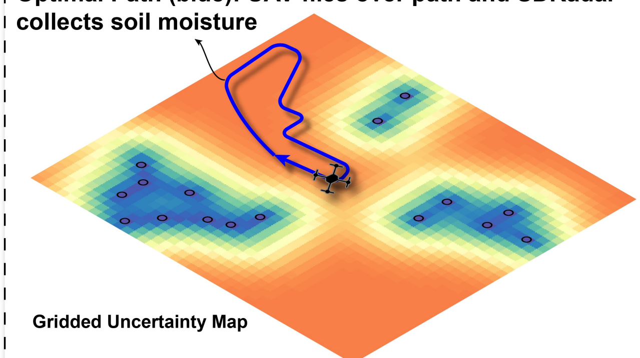
Input:
- Gridded soil moisture uncertainty

Output:
- UAV flight path (Blue path in figure)

Feed back into Step-1:
UAV soil moisture reassimilated into Step 1

(c) (d)

Optimal Path (blue): UAV flies over path and SDRadar collects soil moisture



R. Akbar, S. Prager, A. R. Silva, M. Moghaddam and D. Entekhabi, "Wireless Sensor Network Informed UAV Path Planning for Soil Moisture Mapping," in IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3088658.

Technical and Science Advancements
Soil Moisture Informed UAV Path Planning

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2. Mixed Integer Programming (MIP) to <u>maximize UAV round-trip flight over soil moisture uncertainty map</u>

$$\max \sum_{i,j}^{N} u_{ij} \cdot x_{ij} \;\; ; \quad x_{ij} \in \{0,1\} + \textbf{UAV Flight Constraints} + \textbf{SDRadar Constraints}$$

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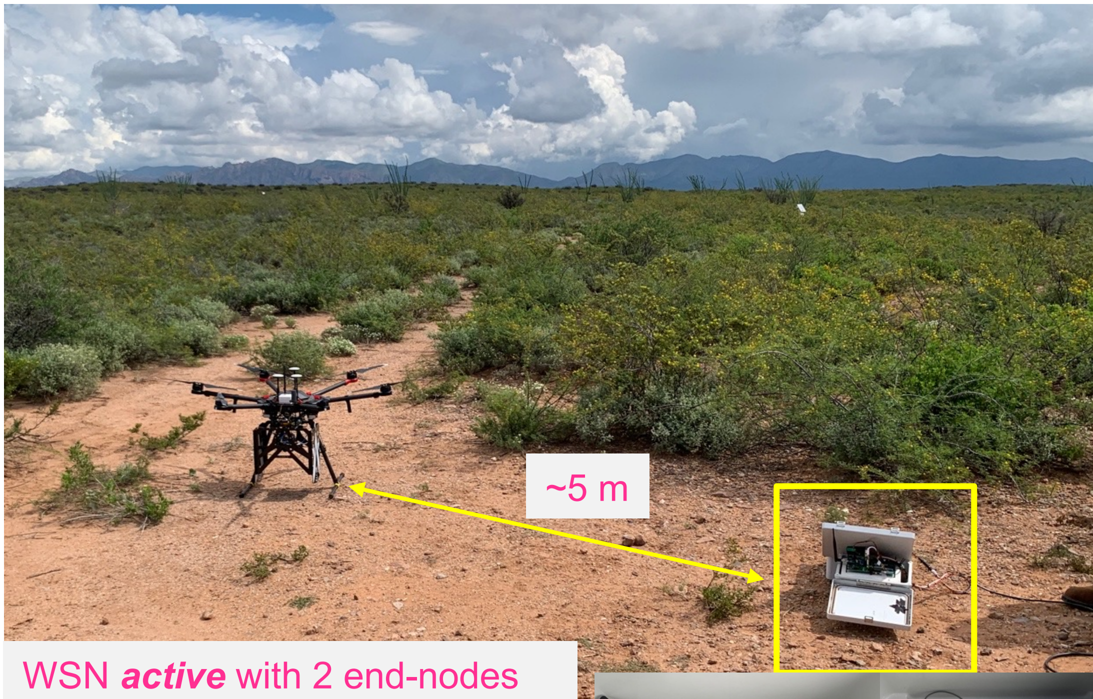
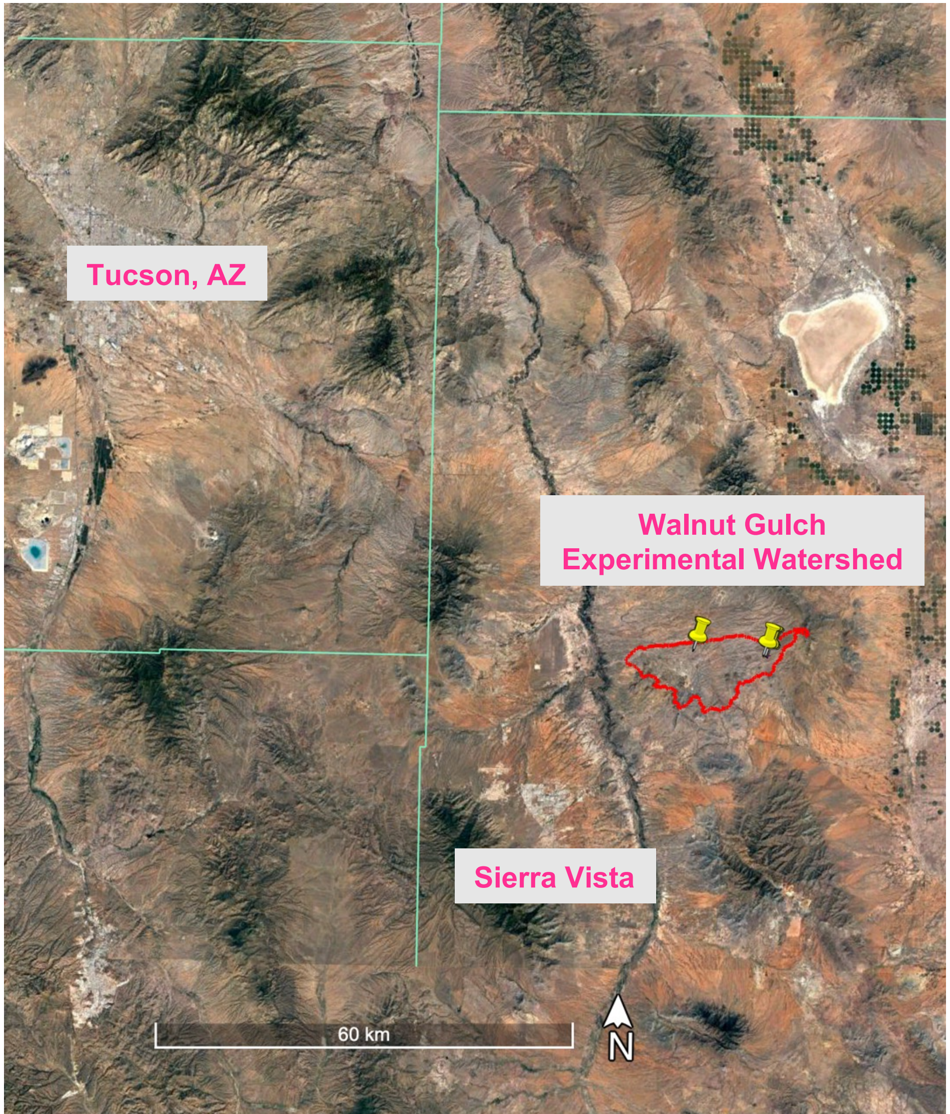
Summary of Accomplishments and Future Plans
UAV-WSN Field Demo (Aug 8-13th 2021)

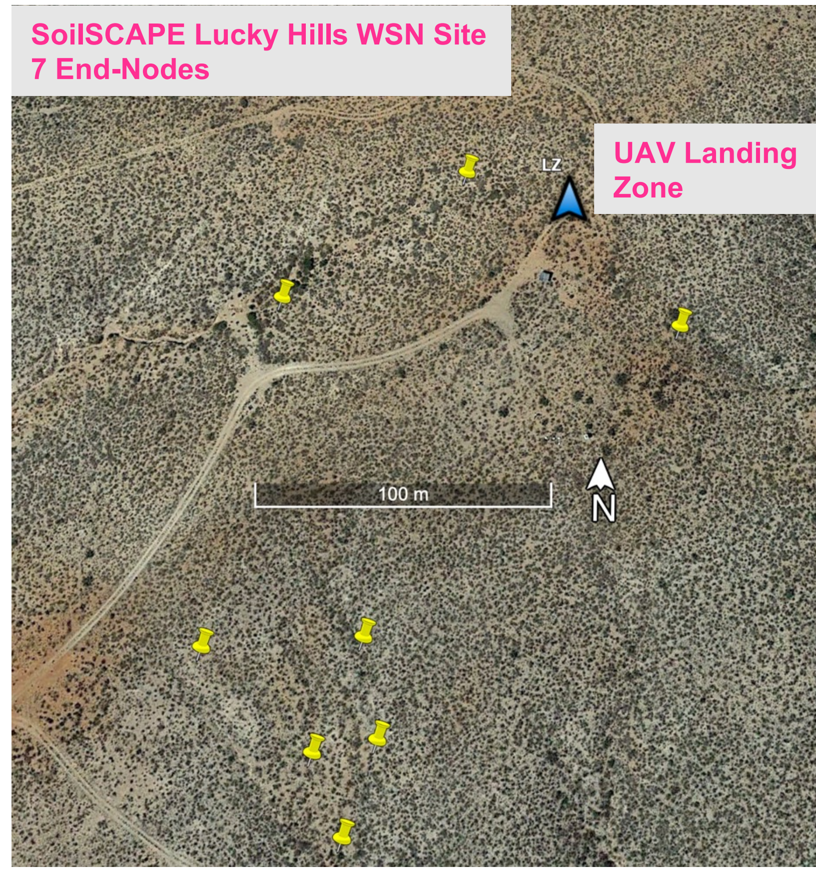
- Custom hardware and software for WSN and UAV parallel operations
- 1st field demo to showcase NOS-like operations



Summary of Accomplishments and Future Plans

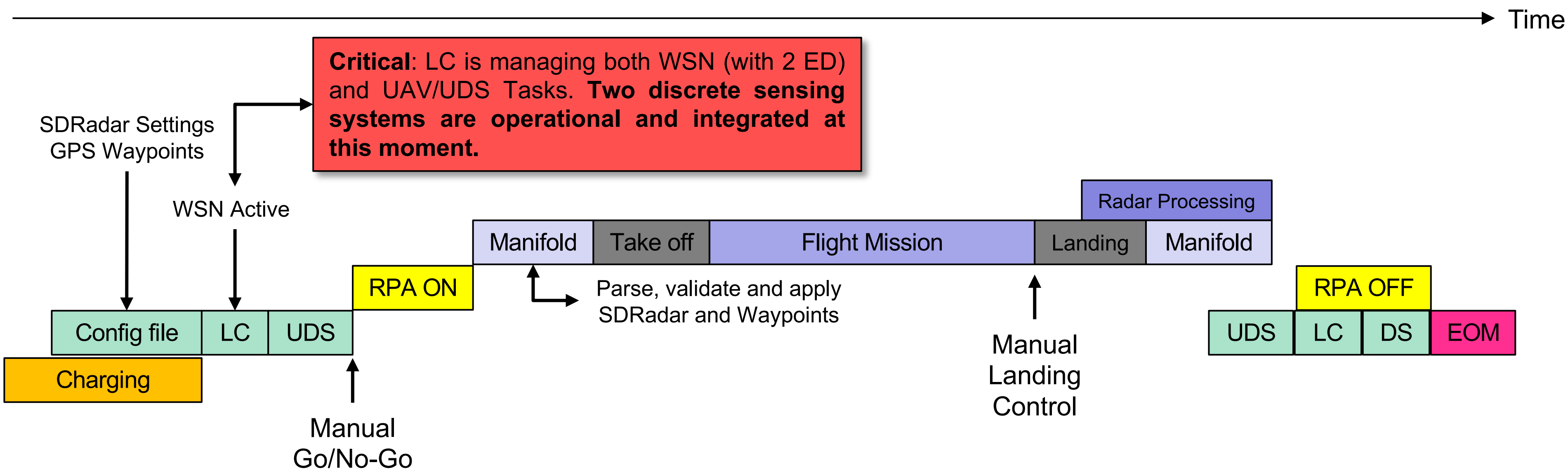
WSN-UAV field demo at Walnut Gulch Experimental Watershed





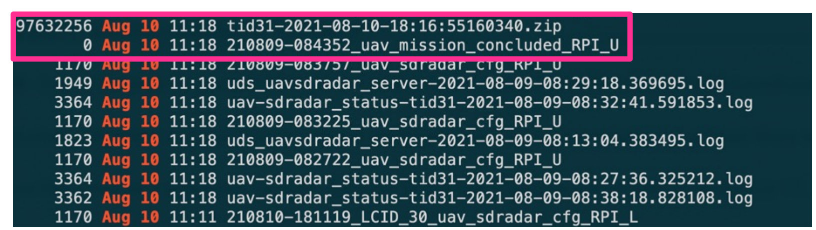
Summary of Accomplishments and Future Plans

Mission Timeline Template



Mission Logs

- LC and UDS config file "breadcrumbs"
- Post Mission:
  - SDRadar
  - UAV Manifold Server
  - Mission Radar Data



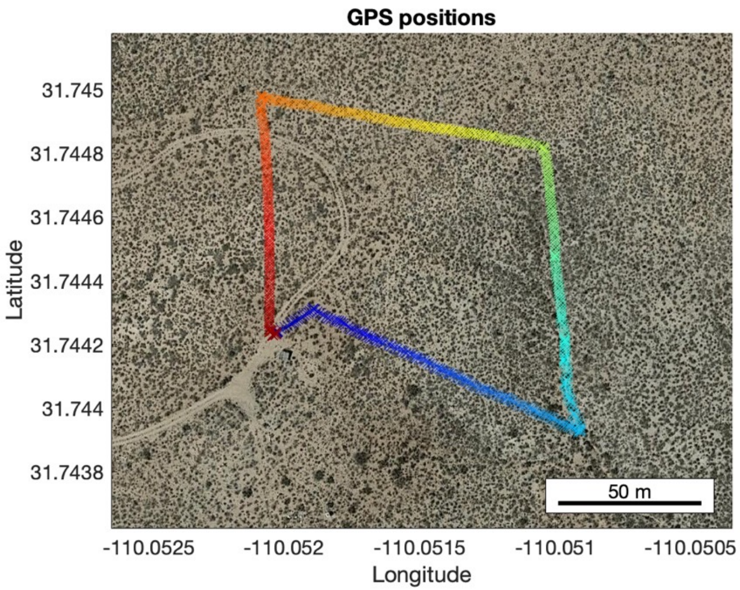
SoilSCAPE Data server

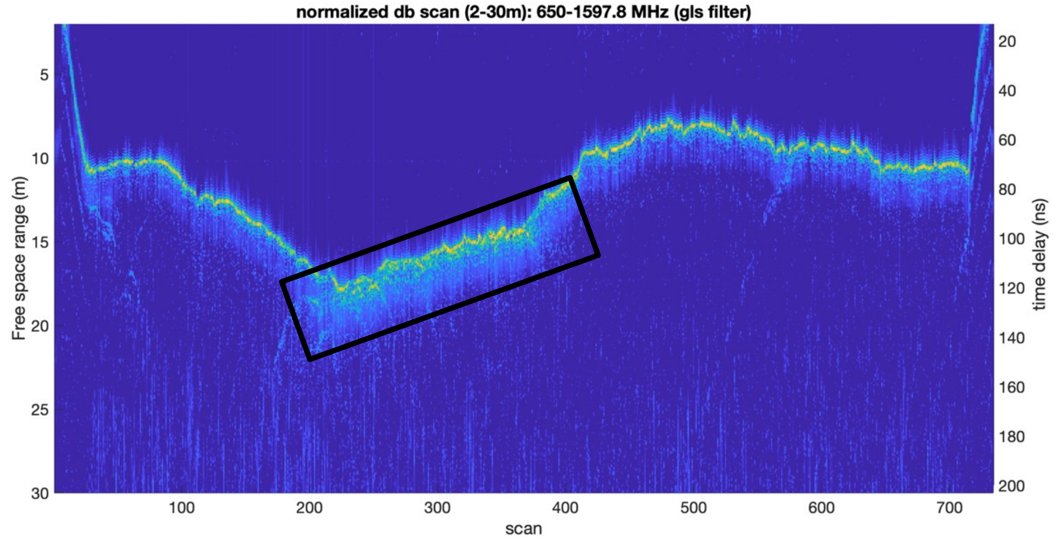
LC: Local Coordinator
UDS: UAV Data server
DS: Data Server
EOM: End Of Mission

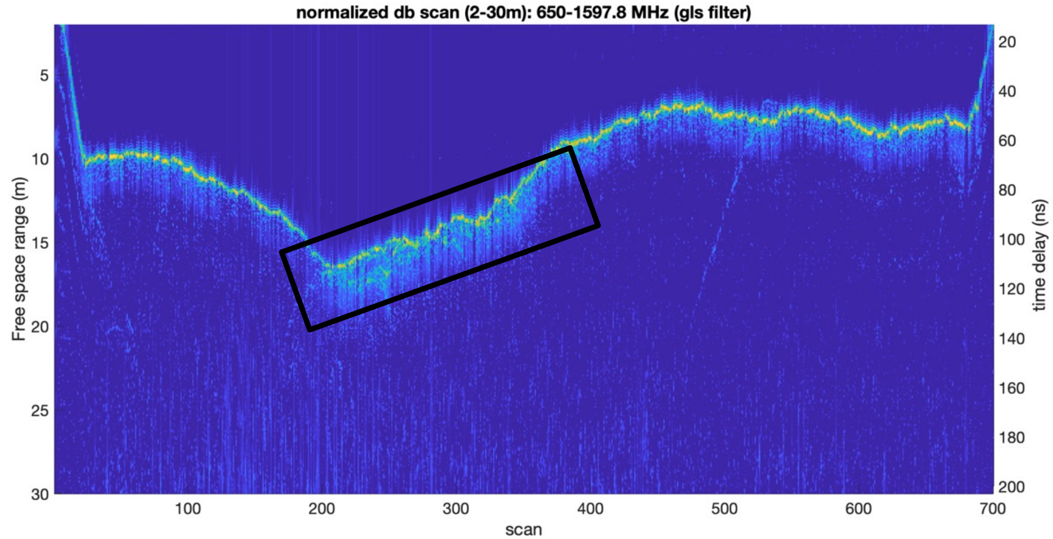
Summary of Accomplishments and Future Plans
Annotated Flight Demo

Example SDRadar Data (P- to L-band)
08/10 - (rain in afternoon) – 08/11

Potential evidence of a subsurface water layer after monsoon rain in local watershed.





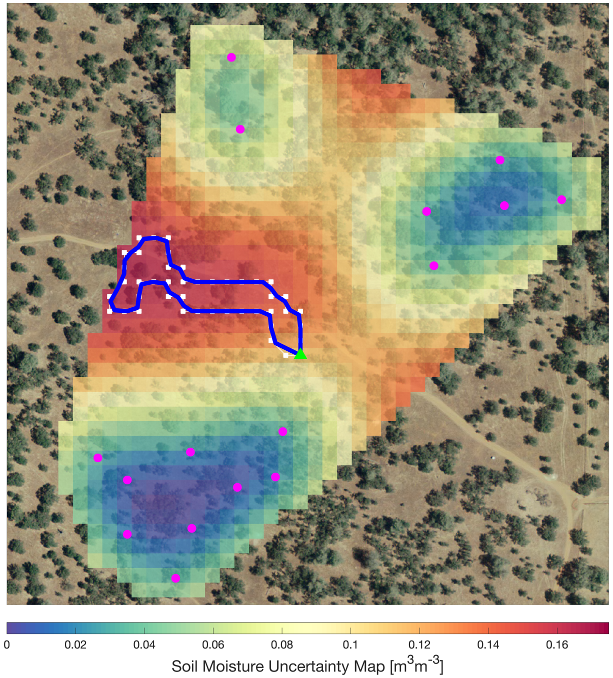


Earth Science Technology Office

Summary of Accomplishments and Future Plans

Preparations for 2nd (& potentially more) field demo(s)

- Streamline mission generation and flight process
  - Less manual control
  - Web interface for way-point generation
- Larger active WSN with 9 wireless nodes
- Generate flight mission using real-time WSN soil moisture data



In a fully integrated and complete SPCTOR implementation:

- Real-time mission generation (way-points) using WSN data
- Autonomous UAV take-off, data collection, and landing.

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Actual or Potential Infusions and Collaborations

Satellite Soil Moisture Cal/Val:

- NASA CYGNSS mission has commissioned SoilSCAPE WSN sites for soil moisture cal/val
  - San Luis Valley, CO: two active SoilSCAPE networks
  - Jornada Rangeland (White Sands), NM planned for 2022
  - Multiple sites in New Zealand planned for 2022
- Fully deployed SPCTOR can provide cal/val data to future NASA Earth science missions:
  - High spatial resolution soil moisture mapping will be relevant to upcoming **NiSAR** mission

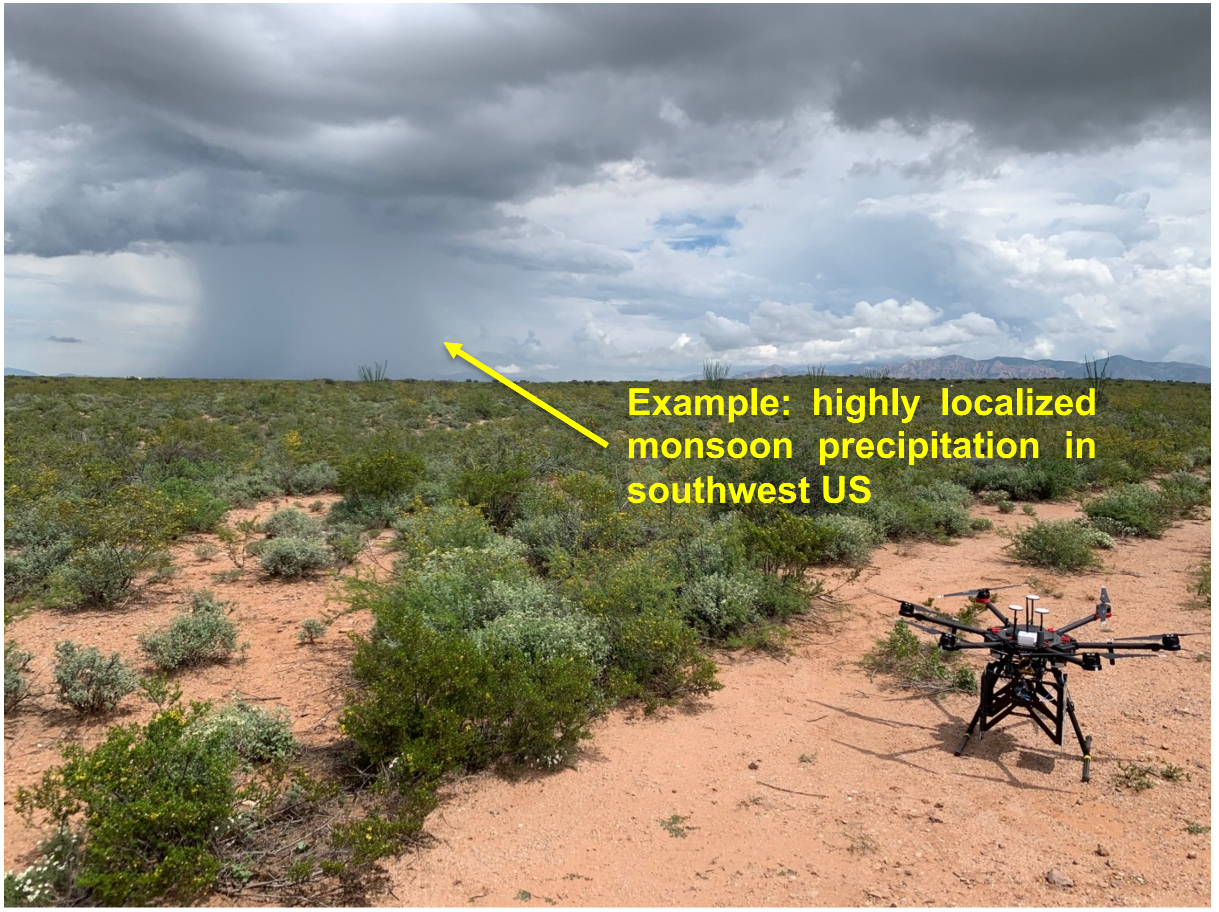
NOS:

- NOS-like collaboration and demonstration in relevant environment with AIST D-SHIELD project (PI: Nag).
- SPCTOR can interface with NOS testbed: taskable UAVs from other NOS nodes.

SPCTOR and NOS in the Real World

Implications of localized monsoon
- Undetected by WSN
- May bias satellite derived soil moisture
- Potentially unseen by Earth looking satellite platforms

Continuation of SPCTOR in Real World:
- Multiple WSN talking to each other and sharing information
- Tasking networks of UAV for map post-monsoon soil moisture
- Informing other NOS assets of ground conditions and observations.
- Other applications include predicting and tracking:
    - Wildfires
    - Snowpack
    - Floods



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List of Publications

Journal papers:

R. Akbar, S. Prager, A. R. Silva, M. Moghaddam and D. Entekhabi, "Wireless Sensor Network Informed UAV Path Planning for Soil Moisture Mapping," in IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3088658.

Prager, Samuel, Graham Sexstone, Daniel McGrath, John Fulton, and Mahta Moghaddam. "Snow Depth Retrieval With an Autonomous UAV-Mounted Software-Defined Radar." IEEE Transactions on Geoscience and Remote Sensing (2021).

Prager, S., M. Haynes, and M. Moghaddam, “Wireless Sub-Nanosecond RF Synchronization for Ultra-Wideband Coherent MIMO Software Defined Radar,” IEEE Trans. Microwave Theory and Techniques, vol. 68, no. 11, pp.4787-4804, Nov. 2020, DOI 10.1109/TMTT.2020.3014876 .

Conference papers:

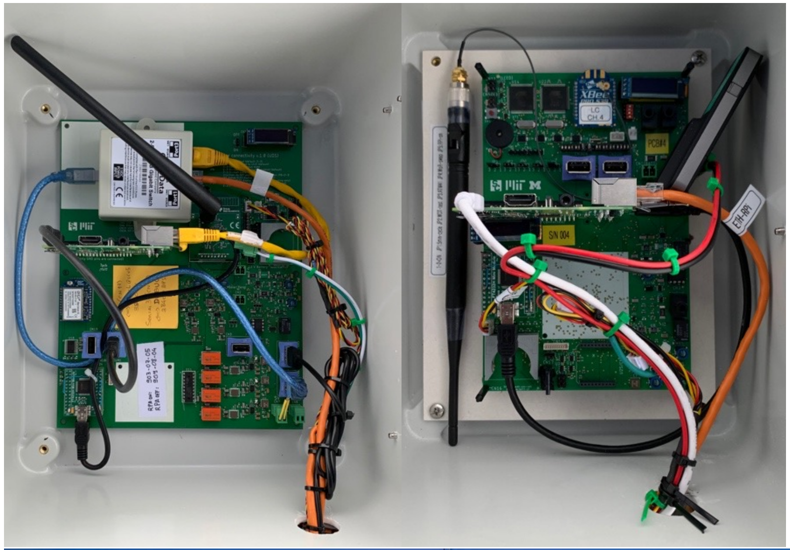
Prager, S., B. Hawkins, and M. Moghaddam, “Arbitrary nonlinear FM waveform construction and ultra-wideband synthesis,” presented at IGARSS’20 online symposium (finalist in Student Paper Prize Competition).

Moghaddam, M., R. Akbar, S. Prager, A. Silva, and D. Entekhabi, “SPCTOR: sensing policy controller and optimizer,” presented at IGARSS’20 online symposium.

Moghaddam, M., R. Akbar, A. Silva, S. Prager, and D. Entekhabi, “Multi-agent multi-scale observations of soil moisture via SPCTOR: sensing policy controller and optimizer,” accepted for presentation at AGU Fall 2020 meeting.

List of Acronyms

AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
AU	Application User
DS	Data Server
ED	End Device
LC	Local Coordinator
LC-RPi	LC Raspberry-Pi
ML	Machine Learning
MOO	Multi-Objective Optimization
MSE	Mean Squared Error
NISAR	NASA ISRO Synthetic Aperture Radar
RZSM	Root Zone Soil Moisture
SDRadar	Software Defined Radar
SMAP	Soil Moisture Active Passive
SoilSCAPE	Soil moisture Sensing Controller and oPtimal Estimator
SPC	Sensing Policy Controller
SPCTOR	Sensing Policy Controller and OptimizeR
SR	Santa Rita
TZ	Tonzi Ranch
UAV	Unmanned Aerial Vehicle
UDS	UAV Data Server connectivity board
WG	Walnut Gulch
WoR	Wake-up on Radio
WSN	Wireless Sensor Network



Ground Stations as a Service (GSaaS) for Near Real-time Direct Broadcast Earth Science Satellite Data

Louis Nguyen(PI, NASA LaRC)
Thad Chee (Co-I, SSAI)
Andrei Vakhnin (Co-I, SSAI)
Jason Barnett (Co-I, BAH)
William Smith, Jr. (Co-I, NASA LaRC)

AIST-20-QRS-0003 Final Technical Review
January 7, 2022

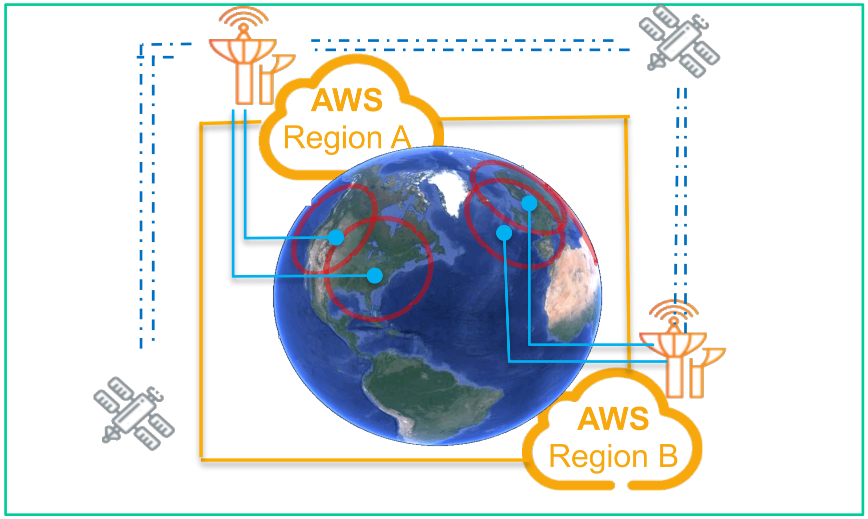
Ground Station as a Service (GSaaS) for Near Real-time Direct Broadcast Earth Science Satellite Data

PI: Louis Nguyen, NASA Langley Research Center

Objective

Develop a Ground Station as a Service (GSaaS) data acquisition and processing framework on Amazon Web Services (AWS) to receive direct broadcast (DB) data from Earth Observing Satellites (EOS) and to significantly reduce data latency associated with acquisition and processing. Near real-time (NRT) EOS data are critical to support weather diagnoses and forecasting, disaster management, airborne science research and other applications. This system framework provides:

- Ability to receive low latency LEO data (ie. MODIS/ VIIRS/ CrIS) without owning/maintaining DB ground station
- Reduce data product latency from 3-6 hours to 20-25min
- Ability to task system for planning, scheduling, reserving, and processing DB data via API services.



Ground Station Observation Network (GSON) using Amazon Ground Station as a Service (GSaaS)

Accomplishments

- Completed satellites onboarding to receive direct broadcast data from NPP, JSPP-1, and AQUA
- Completed ground stations onboarding to receive and process DB data from 8 ground stations located in Ohio, Oregon, Bahrain, Stockholm, Dublin, Hawaii, Cape town and Seoul
- Completed integration of NASA DRL and Univ of Wisconsin CSPP software technology for Level 0 through 3 processing
- Developed Planner and scheduler services to reserve satellite DB over the ground station meeting user specification and requirements
- Developed in cloud scalable Processing Framework to easily process level 0 through 3 products
- Developed a GSON Node with capabilities for the New Observing Strategy Testbed (NOS-T) to schedule, coordinate, receive, process, and deliver low latency DB data through the use of triggers or via GSON API services

Co-Is/Partners: T. Chee, SSAI; A. Vakhnin, SSAI; J. Barnett, Booz Allen Hamilton; W.L. Smith Jr., NASA LaRC

TRL_{in}= 3 **TRL_{out}= 5**

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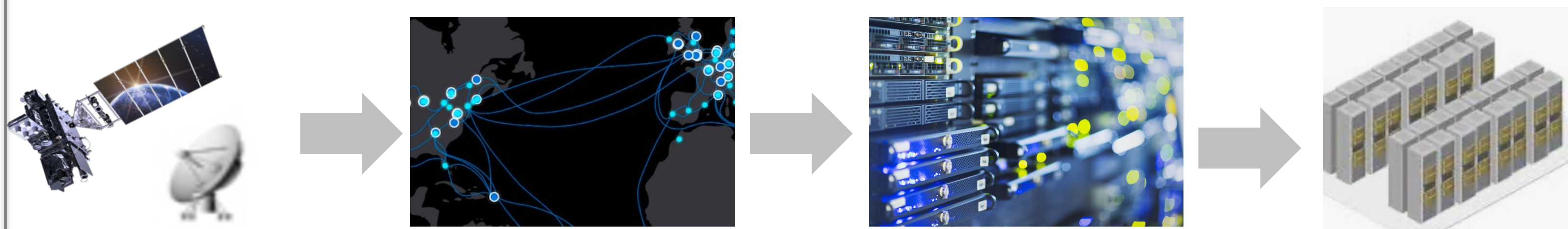
Background and Objectives

Problem: Latencies occur at data acquisition, ground station, data transfer, data center processing and distribution (**1.5 - 3+ hrs**)



Reception at Svalbard GS

Transfer to Data Center

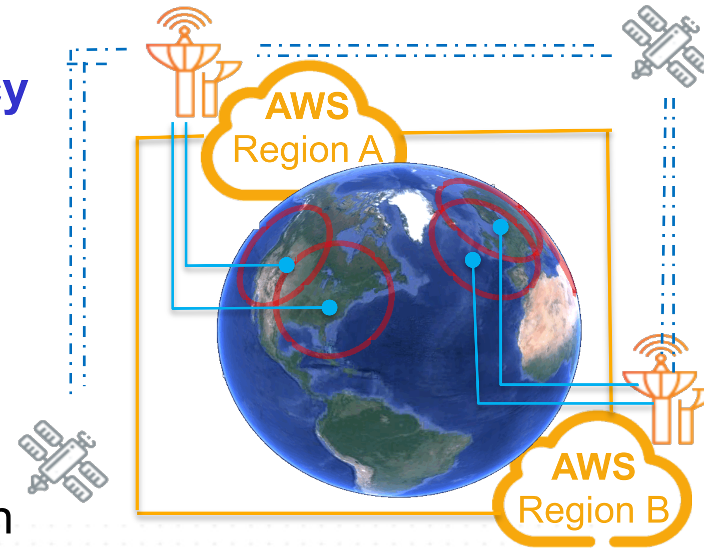
Data Center Processing

Access and Distribution

Objectives: Utilize commercial ground stations to reduce LEO data latency to less **25min** for use in NRT Applications

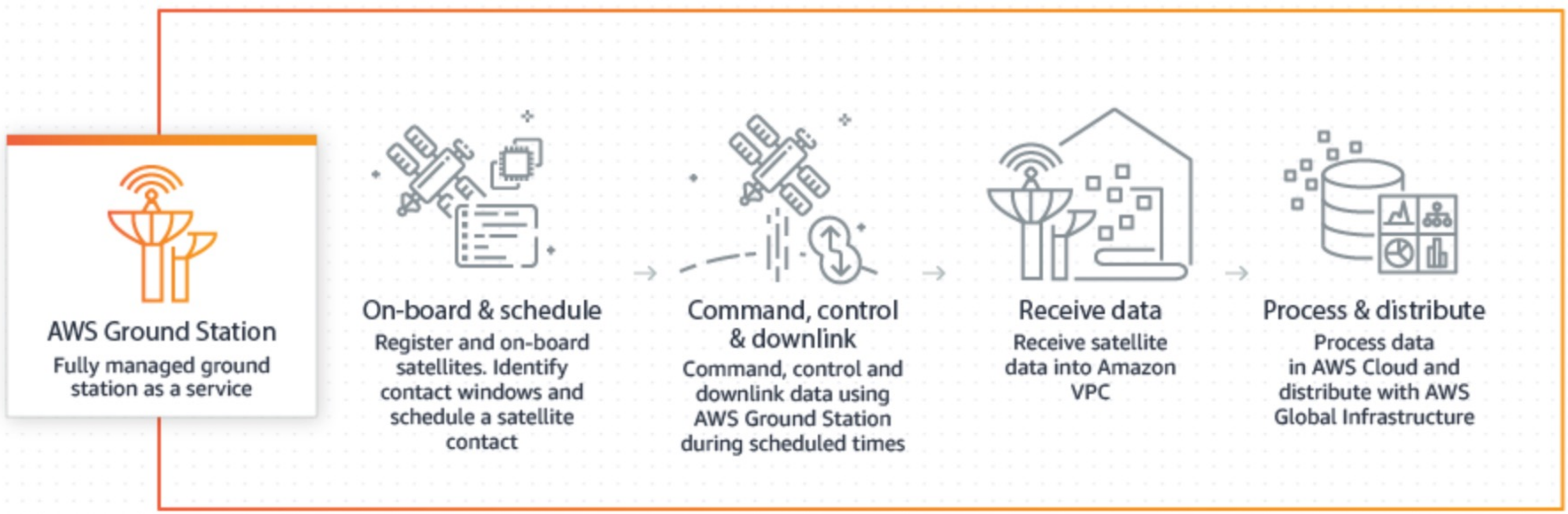
Background and Objectives

Utilize Amazon Ground Station as a Service (GSaaS) and AWS Cloud to reduce data latency



How GSaaS works

- Provides global network of ground stations
- On-boarding and Scheduling
- Downlink direct broadcast data
- Allows uplink for command and control
- DB data received by VPC instance
- Data delivered to S3 for processing/distribution



ESTO Earth Science Technology Office

Background and Objectives

AWS Ground Station Regional Coverage

- Amazon currently have 9 operational GS; expected to expand to over 12
- Antennas capable of receiving X- and S- Band frequencies from LEO and MEO
- Pay as you go service for use of antenna: $3 per min (resv) and $10 for on-demand

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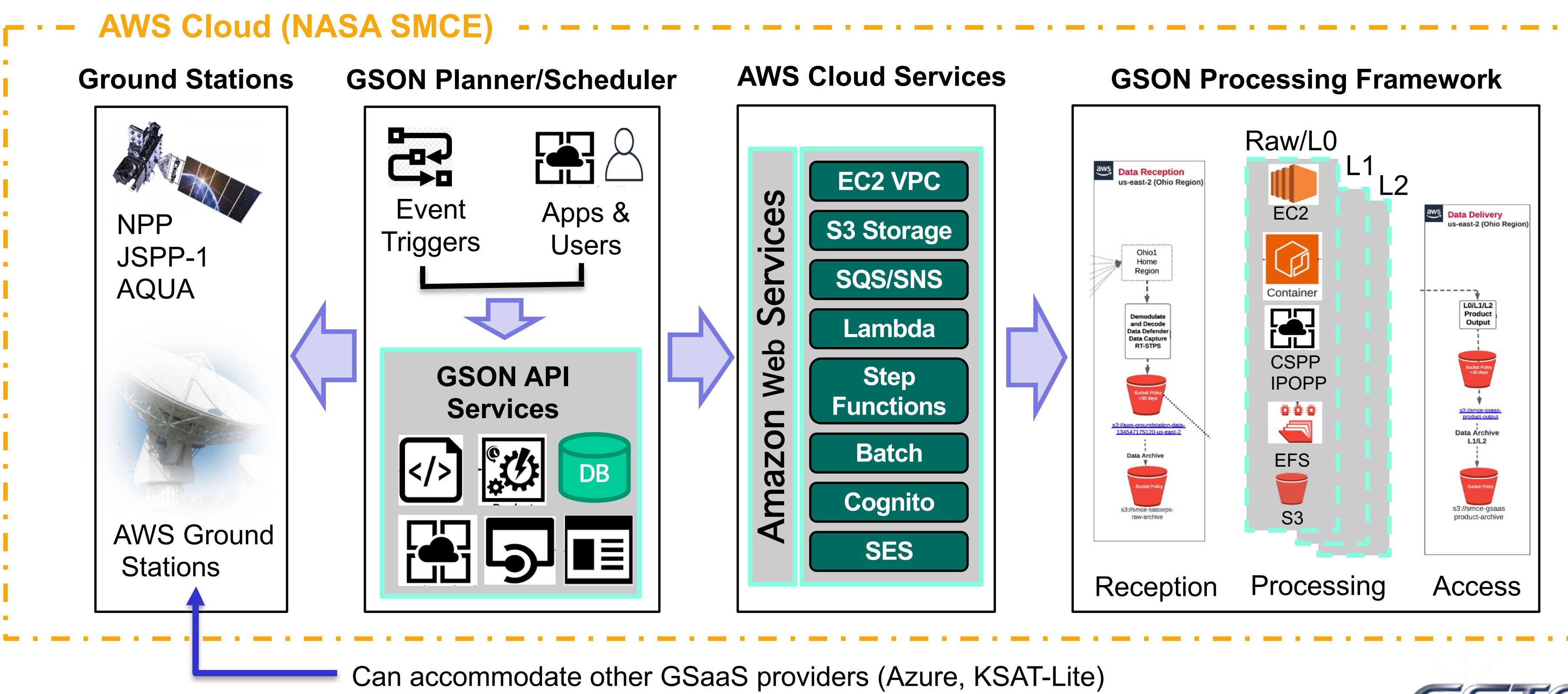
Technical and Science Advancements

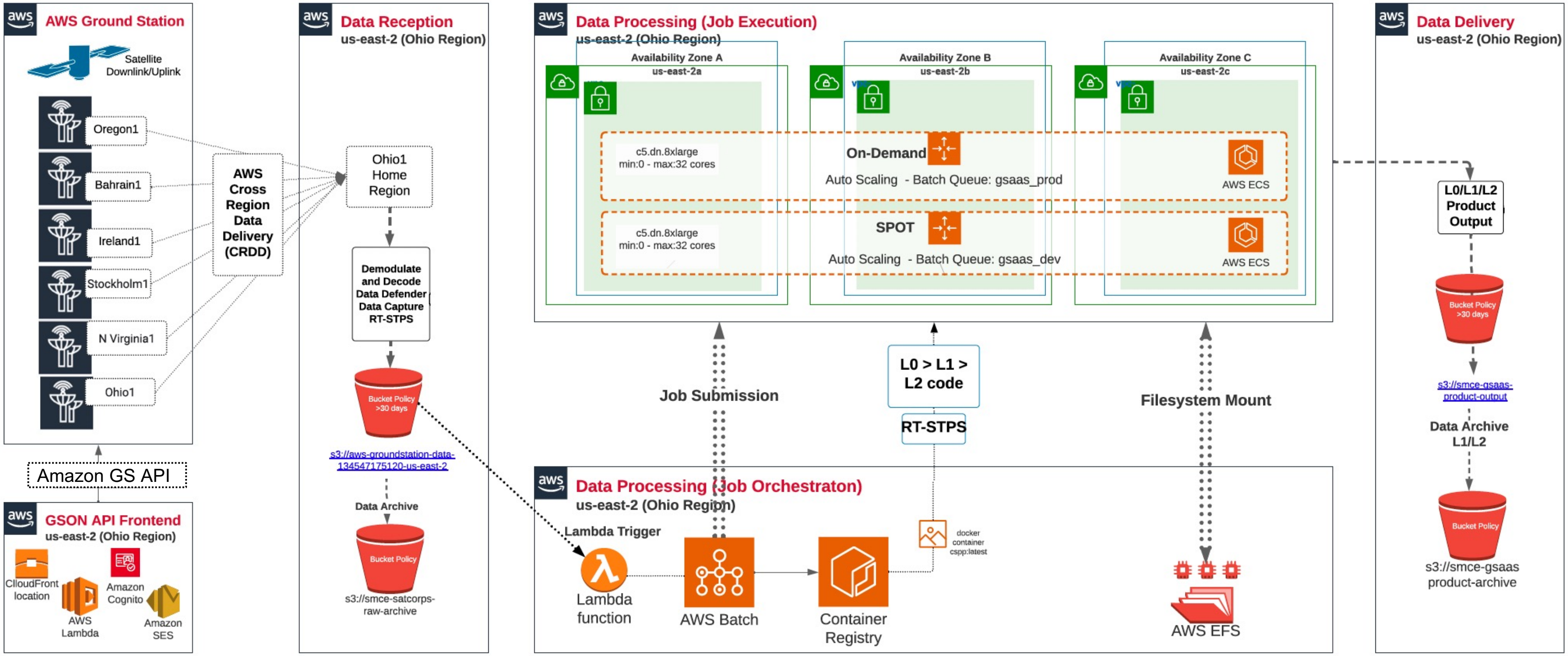
Ground Station Observation Network (GSON) Components:

- Commercial Ground Stations (Amazon)
- **GSON Planner and Scheduling Services (tasks/job orchestration)**
- Amazon Cloud and CloudWatch Services
- **GSON Processing Framework**



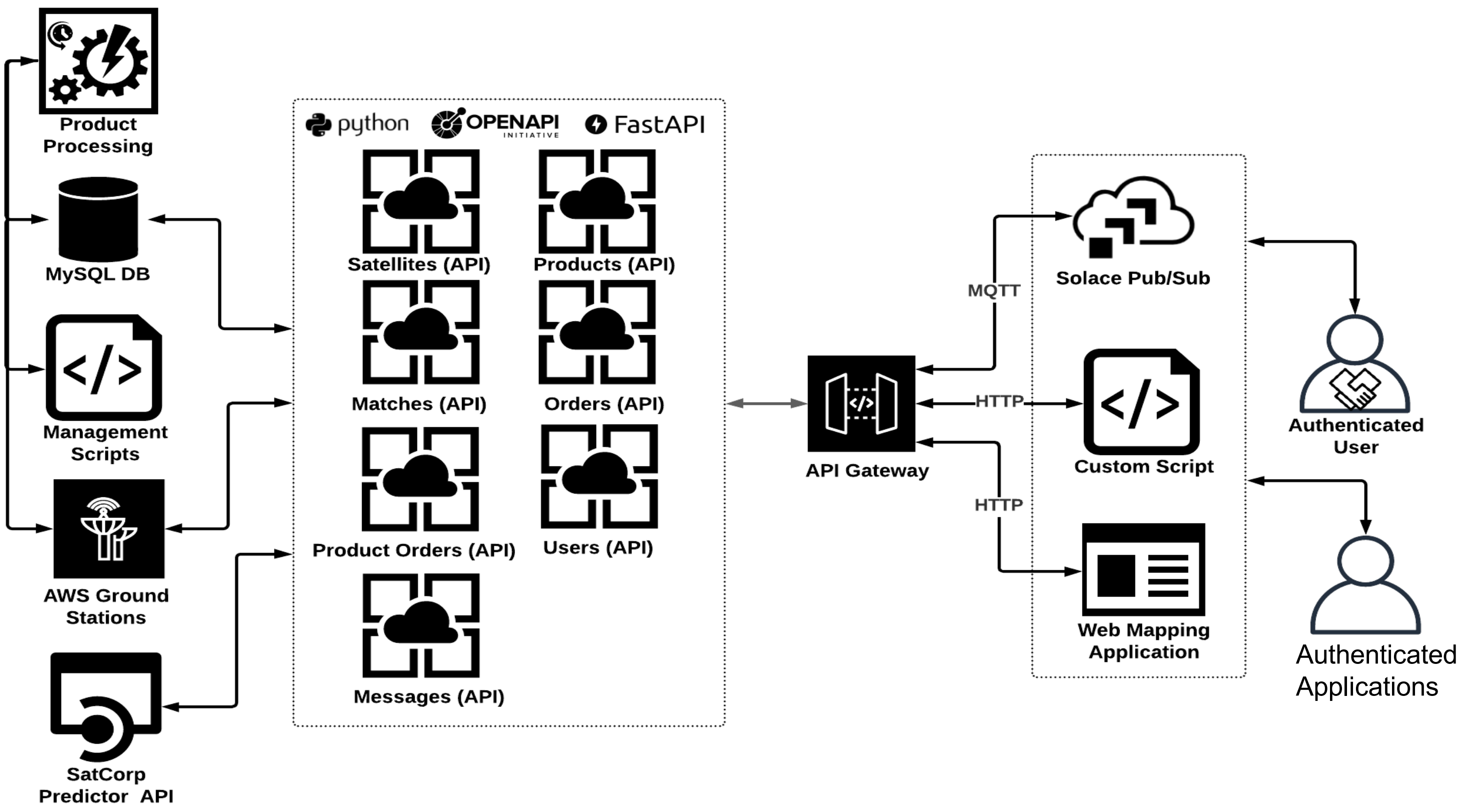
Technical and Science Advancements

GSON Full System Architecture Diagram



GSON Planner and Scheduling Services (tasks/job orchestration)

GSON Service Layer Architecture

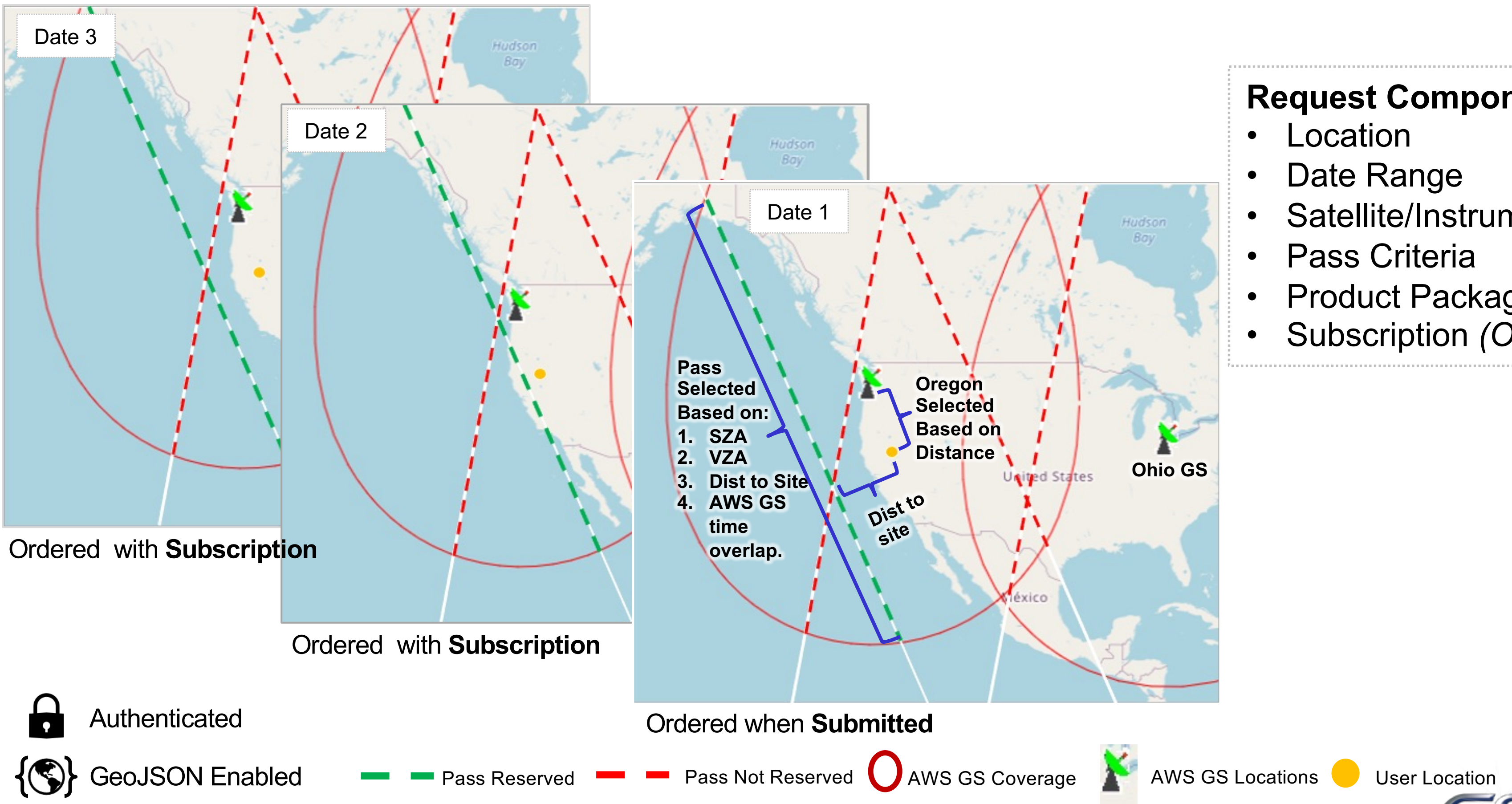


Technical and Science Advancements

GSON Planner and Scheduling Services (tasks/job orchestration)

Multiple Date Request for ‘All Dates’ and ‘Subscription’

Visual representation of API Single Point Capabilities



Request Components

- Location
- Date Range
- Satellite/Instrument
- Pass Criteria
- Product Package
- Subscription *(Optional)*

Authenticated

GeoJSON Enabled

Technical and Science Advancements

GSON Planner and Scheduling Services (tasks/job orchestration)

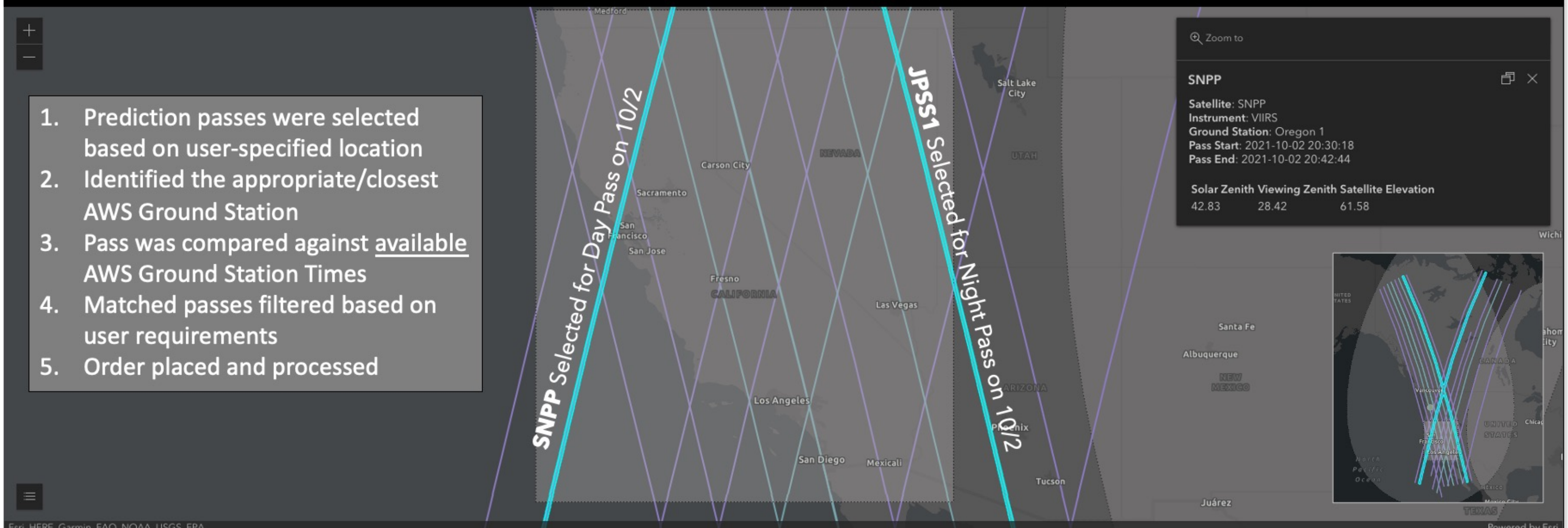
Visual representation of API **Bounding Box** Capabilities

DAY Passes (SZA: 0-90)

Satellite	Predicted Start	Predicted End	Solar Zenith	Viewing Zenith	Distance To Site	Elevation
JPSS1	10/2/21 19:33	10/2/21 19:53	41.08	68.05	1438.98	21.95
SNPP	10/2/21 20:28	10/2/21 20:43	42.83	28.42	392.45	61.58

NIGHT Passes (SZA: 90 – 180)

Satellite	Predicted Start	Predicted End	Solar Zenith	Viewing Zenith	Distance To Site	Elevation
SNPP	10/2/21 9:02	10/2/21 9:22	140.62	45.65	714.13	44.35
JPSS1	10/2/21 9:52	10/2/21 10:12	133.65	27.96	385.14	62.04
SNPP	10/2/21 10:42	10/2/21 11:02	125.1	67.93	1433.08	22.07



Available Passes (Features: 16, Selected: 2)

	Satellite	Instrument	Station	Start	End	SZA	VZA	Distance to Site
☐	SNPP	VIIRS	Oregon 1	2021-10-01 20:49:03	2021-10-01 21:01:33	43.85	1.16	14.97
☐	SNPP	VIIRS	Oregon 1	2021-10-01 20:49:03	2021-10-01 21:01:33	43.87	1.19	15.29
☑	JPSS1	VIIRS	Oregon 1	2021-10-02 09:53:33	2021-10-02 10:06:17	133.65	27.96	385.14
☑	SNPP	VIIRS	Oregon 1	2021-10-02 20:30:18	2021-10-02 20:42:44	42.83	28.42	392.45
☐	JPSS1	VIIRS	Oregon 1	2021-10-03 09:34:46	2021-10-03 09:47:41	136.77	1.66	21.31

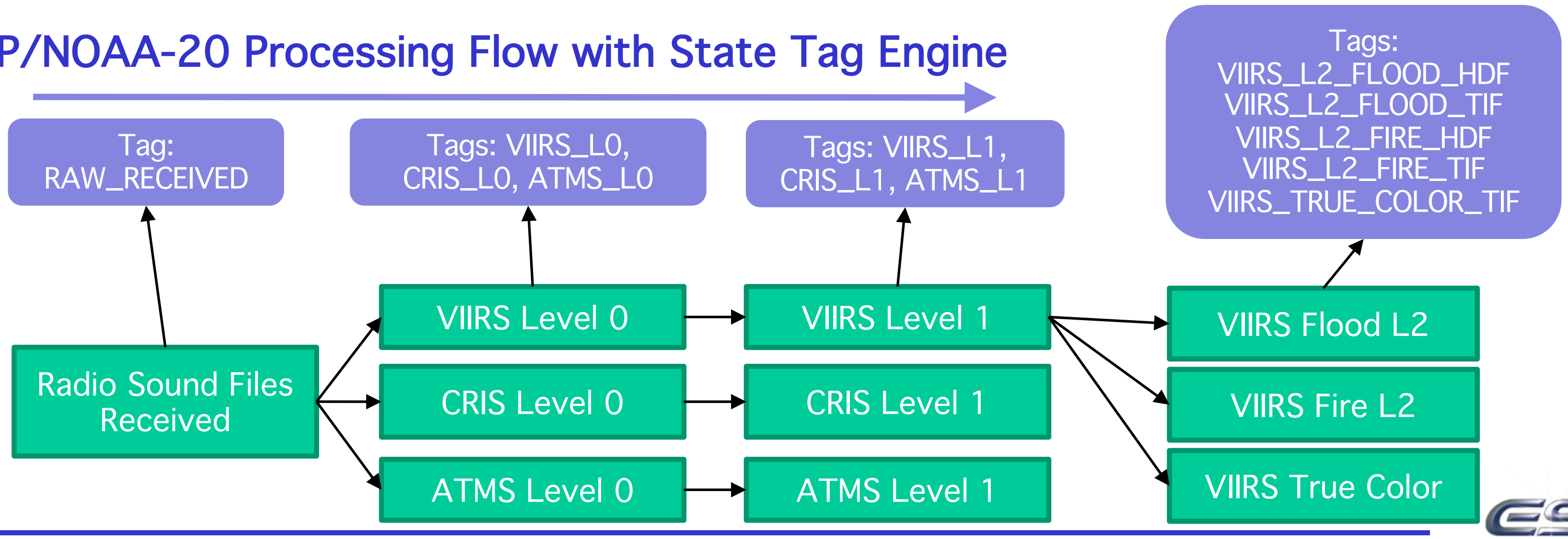
ESTO Earth Science Technology Office

Technical and Science Advancements

GSON Scalable Processing Framework

- Scalable framework provides customization
- Designed for efficient high-speed processing
- Can accommodate any satellites or instruments or data sources
- Bring you own Algorithm (BYOA)
  - User can implement custom science algorithm (containers)
- Enables Open Science through the sharing of data, algorithms, and knowledge
- Utilize scalable multicore instances to Parallel process workflows

NPP/NOAA-20 Processing Flow with State Tag Engine



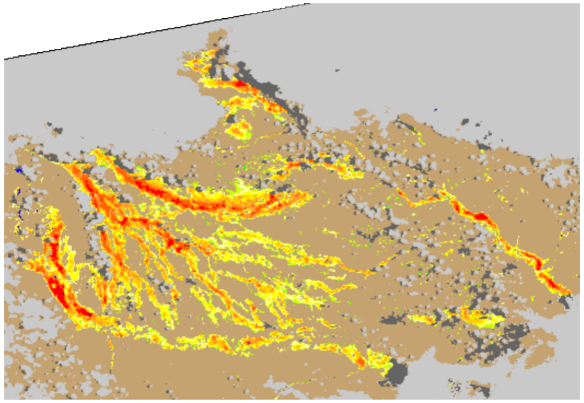
Technical and Science Advancements

Prototype VIIRS Node for NOS-T Flood Demonstration

- **Support New Observing Strategies Testbed (NOS-T) historical flood demo Spring 2021 and real-time demo Fall 2021**
- **Reduce latency; Delivery of products (L0-L3) < ~25min**

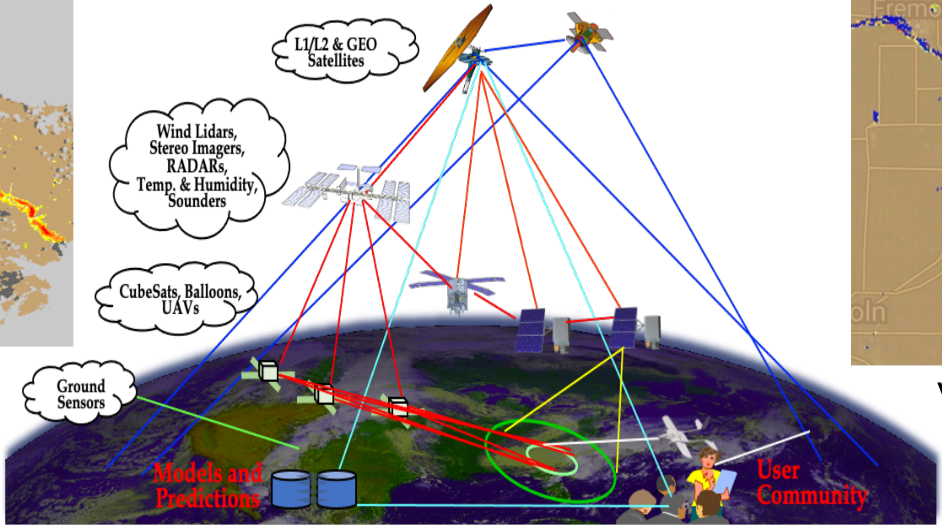
Features:

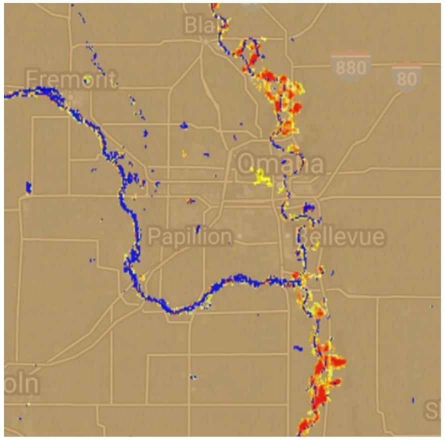
- Triggered by events (stream gauge and/oor model)
- Triggered by user/app via GSON Service API
- Automated scheduling and job orchestration (reception & processing workflows)
- Distribution via S3, HTTPS, and ARC-GIS portal endpoints



Floodwaters over South Africa derived from NPP VIIRS

New Observing Strategies (NOS)





VIIRS Flood Detection Mississippi Basin

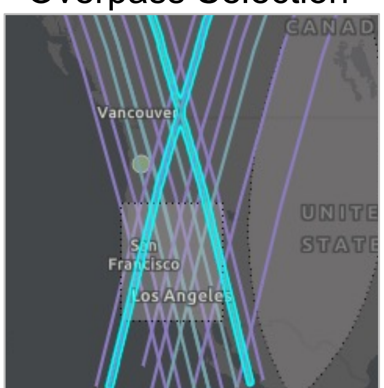
Technical and Science Advancements

Low Latency VIIRS for WRF-SFIRE Forecasting Demo

- Conducted proof-of-concept demonstration on Oct 1-8, 2021; GSON delivered low latency VIIRS Active Fires detections (<13 min) covering a defined bounding box
- The Weather Research Forecasting – Spread FIRE (WRF-SFIRE, Disasters Program) ingested the low latency VIIRS data to initialize fire perimeter of the KNP Fire
- WRF-SFIRE produced 48 hour forecast of fuel moisture, fires spread, and smoke at 9 & 21z along side with regular latency data from LANCE and LAADS at 0 & 12z
- Results were qualitatively similar; hence low latency data can successfully be assimilated in WRF-SFIRE; Improvement/accuracy comparison will be conducted

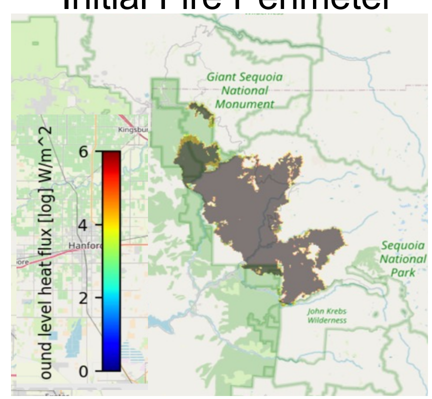
Oct 4, 2021 WRF-SFIRE 24hr Forecast using GSON Low Latency VIIRS Active Fires

Overpass Selection

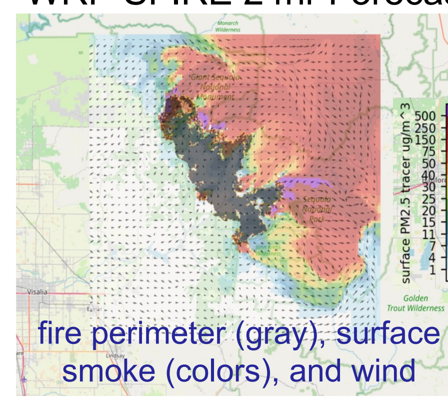


VIIRS Active Fires

Initial Fire Perimeter



WRF-SFIRE 24hr Forecast



WRF-SFIRE Results courtesy of Kyle Hilburn, CSU

Technical and Science Advancements

Low Latency VIIRS for WRF-SFIRE Forecasting Demo

- Data Delivery via S3 and HTTPS in ~12min latency

- Mirrored LANCE data structure (file, directory, & format)

- SMCE AWS https: satcorps-larc.com/archive/allData/5001/VNP03IMG_NRT/2021/125/

GSaaS/GSON File Pickup

Directory Listing

GITCO_npp_d20210505_t1857111_e1858353_b49336_c20211001162522584832_cspp_de
GITCO_npp_d20210505_t1858365_e1900007_b49336_c20211001162520084488_cspp_de
GITCO_npp_d20210505_t1900019_e1901261_b49336_c20211001162519483180_cspp_de
GITCO_npp_d20210505_t1901273_e1902515_b49336_c20211001162524332138_cspp_de
GITCO_npp_d20210505_t1902527_e1904151_b49336_c20211001162523737833_cspp_de
GITCO_npp_d20210505_t1904163_e1905405_b49336_c20211001162526722017_cspp_de
GITCO_npp_d20210505_t1905417_e1907059_b49336_c20211001162527129329_cspp_de
GITCO_npp_d20210505_t1907071_e1908313_b49336_c20211001162526719382_cspp_de

End of listing.

Overpass (

Click on the overpass you v

Satellite	Date/Time	Status	Contact ID	D		
JPSS1	2021-10-08 21:06:24	Oregon 1	a1a679d0-e4e2-4f64-98f7-03dcae3a847d (384)			
JPSS1	2021-10-08 09:43:21	Oregon 1	0e6e5899-3c75-4da0-9083-f8c1931b91ee (383)			
SNPP	2021-10-07 20:36:33	Oregon 1	a501aeda-2eb5-4bee-b6b0-df14797ec3c6 (382)			
JPSS1	2021-10-07 09:59:47	Oregon 1	761af3ea-8b5a-4a1a-a517-45fbe2eacc27 (381)			
SNPP	2021-10-06 20:55:22	Oregon 1	35378800-d230-4463-9fe1-bc27725127a3 (380)			
SNPP	2021-10-06 09:29:10	Oregon 1	7a9e63b2-6cd0-41b0-b593-04451d1154f2 (379)			
JPSS1	2021-10-05 20:23:26	Oregon 1	e02fcddc-2a70-46e0-a4ed-90ddb9c24d1a (378)			
JPSS1	2021-10-05 08:57:08	Oregon 1	16ea0bb3-c501-4615-801d-fbf93b17cdac (377)			
JPSS1	2021-10-04 20:42:08	Oregon 1	b23ab6f5-f6be-4753-9c18-576889a0f204 (376)			
JPSS1	2021-10-04 09:15:55	Oregon 1	9f599ad5-c182-45c9-858f-57d624f68d8e (375)			
JPSS1	2021-10-03 21:01:01	Oregon 1	1faaa064-3305-4d2c-ade9-786cfe306a35 (374)	Fire Test Overpass	Timing Details	Map
JPSS1	2021-10-03 09:34:46	Oregon 1	2f7ef360-f24b-405b-8f93-d27ac230f52b (373)	Fire Test Overpass	Timing Details	Map
SNPP	2021-10-02 20:30:18	Oregon 1	f238d1d3-e831-4454-81a4-a9e3aa3bed98 (372)	Fire Test Overpass (SNPP)	249	Map
JPSS1	2021-10-02 09:53:33	Oregon 1	2a4a19ab-77ab-4d3e-bebd-316656653894 (371)	Fire Test Overpass	Timing Details	Map
SNPP	2021-10-01 20:49:03	Oregon 1	09a465fa-5d6a-4fb9-8e67-3ff4d9f158c3 (369)	Test processing - do not use for statistics or such.	249	Map
SNPP	2021-10-01 20:49:03	Oregon 1	ce5efc93-511c-41e1-ae58-035330a83d13 (370)	Fire Test Overpass (SNPP)	244	Map
SNPP	2021-09-30 21:07:03	Oregon 1	09a465fa-5d6a-4fb9-8e67-3ff4d9f158c3 (365)	Test processing - do not use for statistics or such.	249	Map
SNPP	2021-09-30 21:07:03	Oregon 1	09a465fa-5d6a-4fb9-8e67-3ff4d9f158c3 (366)	Test processing - do not use for statistics or such.	249	Map

End-to-end Timing Table

Date/Time	Satellite	Preprocess (PCAP, VITA-49, RT-STPS)	L0 -> L1	L1 -> L2 M-/I-Band Fire Algorithm	All (including S3 and Archive Update)
10/1 20:49	SNPP	-	-	-	-
10/2 9:53	JPSS1	4m 6s	8m 26s	52/51s	13m 28s
10/2 20:30	SNPP	4m 9s	3m 28s	21/25s	12m 36s
10/3 9:34	JPSS1	4m 11s	3m 50s	30/33s	13m 39s
10/3 21:01	JPSS1	4m 4s	3m 24s	22/32s	12m 45s
10/4 9:28	JPSS1	4m 3s	3m 33s	28/29s	12m 59s
10/4 20:42	JPSS1	4m 10s	4m 5s	29/28s	13m 40s
10/5 8:57	JPSS1	3m 53s	3m 42s	38/31s	12m 44s
10/5 20:23	JPSS1	4m 3s	3m 24s	27/32s	11m 35s
10/6 9:29	SNPP	4m 11s	2m 52s	24/32s	11m 31s
10/6 20:55	SNPP	4m 0s	4m 4s	22/25s	11 m 23s
10/7 9:59	JPSS1	4m 5s	2m 56s	30/22s	10m 34s
10/7 20:36	SNPP	4m 7s	3m 4s	25/30s	12m 11s
10/8 9:43	JPSS1	3m 21s	4m 1s	30/26s	13m 48s
10/8 21:06	JPSS1	4m 1s	3m 13s	24/27s	9m 6s

ESTO Earth Science Technology Office

Presentation Contents

- Background and Objectives
- Technical and Science Advancements
- Summary of Accomplishments and Future Plans
- Actual or Potential Infusions and Collaborations
- Publications - List of Acronyms

Summary of Accomplishments and Future Plans

- Designed and deployed GSON on Amazon to receive and process Direct Broadcast data using Amazon Ground Stations
  - Planner and Scheduler services
  - Scalable Processing Framework
  - Captured, process, and deliver Flood products under 25mins and Fires under 12min

- Conducted NOS-T historical flood demonstration (Spr 2021)

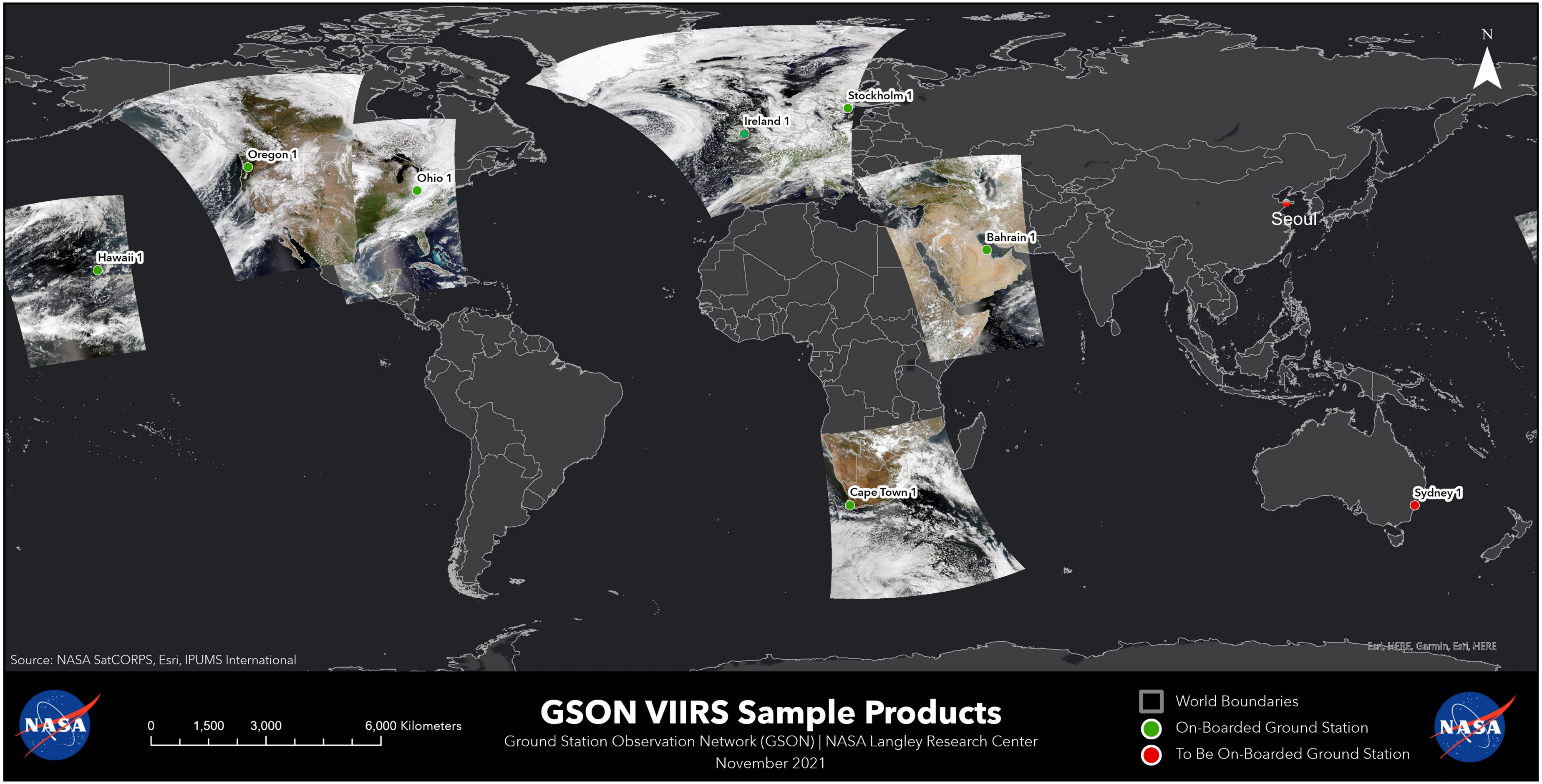
- Conducted WRF-SFIRE wildfires demonstration (Fall 2021)

- Conducted NOS-T real-time flood demonstration (Late Fall 2021)
  - Flood Model triggered GSON Node to produce VIIRS Flood products

Summary of Accomplishments and Future Plans

Conducted successfully VIIRS DB data reception at Amazon GS using GSON

- Ohio, Oregon, Bahrain, Stockholm, Dublin, Hawaii, Cape Town
- Sydney, Seoul



Summary of Accomplishments and Future Plans

- Future Plans
  - Participate in future NOS-T demonstration (when needed)
    - Low Latency ground station Node
  - Expand beyond Amazon Ground Station for global coverage
    - KSATlite, Azure Orbital
  - Support wildfires Summer/Fall 2022

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Actual or Potential Infusions and Collaborations

- In collaboration with Kyle Hilburn at CSU to support the Weather Research Forecasting – Spread FIRE (WRF-SFIRE)

- In collaboration with NASA LANCE (Karen Michael) for technology adoption
    - Infusion of GSON on the NASA Science Cloud to produce parallel low latency VIIRS Fire product stream during 2022 fire season

- NASA New Technology Report (NTR) will be submitted
    - enables technology to be transfer

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Publications

[1] Nguyen, L., T.L. Chee, A.Vakhnin, A.J.Barnett, and W.L. Smith. “Ground Stations as a Service (GSaaS) for Near Real-time Direct Broadcast Earth Science Satellite Data” in *Earth Science Technology Forum (ESTF)*, June 10, 2021.

[2] Smith, B., S. Kumar, L. Nguyen, T.L. Chee, J. Mason, S. Chien, C. Frost, R. Akbar, M. Moghaddam, A. Getirana, P. Grogan, and L. Capra. “Demonstrating a New Flood Observing Strategy on the NOS Testbed” in *The International Geoscience and Remote Sensing Symposium (IGARSS) 2022 Conference: Distributed Observing Systems: Demonstrations and Preliminary Results*, July 2022.

[3] Nguyen, L., T.L. Chee, A.Vakhnin, A.J.Barnett, and W.L. Smith. “Ground Station Observation Network (GSON) for Low Latency Direct Broadcast Data Products” in *NASA New Technology Reporting (NTR)*, submission in progress 2022.

List of Acronyms

• EOS	Earth Observing Satellite
• GSaaS	Ground Station as a Service
• DB	Direct Broadcast
• GSON	Ground Station Observation Network
• LEO	Low Earth Orbiting
• AWS	Amazon Web Services
• GS	Ground Station
• NRT	Near Real-time
• DRL	Direct Readout Laboratory
• NOS-T	New Observing Strategy Testbed
• CSPP	Community Satellite Processing Package
• NPP	National Polar-orbiting Partnership
• NOAA	National Oceanic and Atmospheric Administration
• JSPP	Joint Polar Satellite System
• MODIS	Moderate Resolution Imaging Spectroradiometer
• VIIRS	Visible Infrared Imaging Radiometer Suite
• CrIS	Cross-track Infrared Sounder
• CRDD	Cross Region Data Delivery
• API	Application Programming Interface

Acknowledgement

Thank you!

ESTO
AIST
Jacqueline Le Moigne